Chapter 5 Electromechanical Actuators

5.1 Electromechanical actuators: concept and types (Servomotor, stepper motor, DC motors, Solenoid Actuators, Brushless DC motor), Concept and generalized block diagram of Servo system
5.2 DC servo system: functional diagram, potentiometer as error detector, DC servo motor - characteristics, difference from a normal DC motor
5.3 AC servo system: functional diagram, synchro as error detector, AC servo motor - characteristics, difference from a normal 2 phase induction motor
5.4 Stepper motor (PM and variable reluctance type): Working and applications
5.5 Principle and working of Solenoid Actuators and Brushless DC motor

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1. Electromechanical actuators

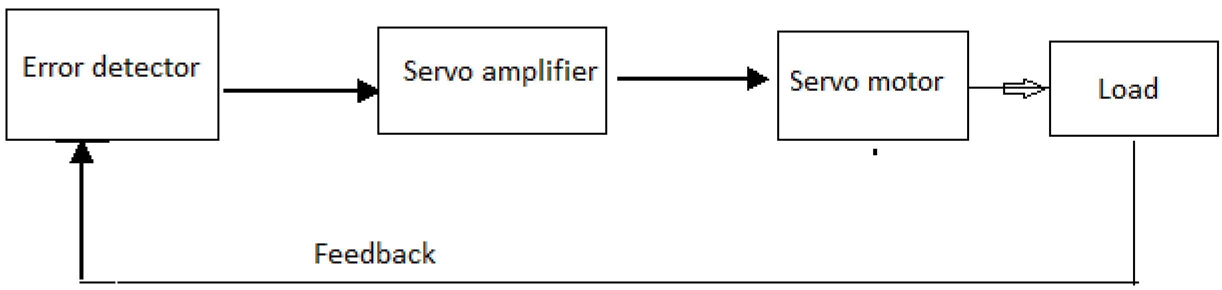
- The output of the controller is usually a small energy signal. The actuator translates the small energy signal of the controller into a larger energy action on the process. It is known as actuator because it uses the controller signal to actuate the final control element.
- If a valve is used to control fluid flow, some mechanism must physically open or close the valve. If a heater is to warm a system, some device must turn the heater on or off or vary its excitation. These are examples of the requirements for an actuator in the process-control loop.
- Examples for actuators are solenoid and electrical motors.

2. Motor

- A motor converts electrical energy into mechanical energy. Examples of various types of motors are DC motor, AC motor, BLDC motor and Servo motor (which consist of AC, DC and stepper motor). Motor consists of a stationary part called stator and rotary part called rotor to which the load is connected. The interaction of two magnetic fields generates a rotating force called Torque which rotates the rotor.

3. Servo system: definition and generalized block diagram

- Servo system is defined as an automatic feedback control system working on error signals giving the output as mechanical position, velocity or acceleration.
- The error signals are amplified to drive the motors, which are coupled to the output.
- Block diagram:



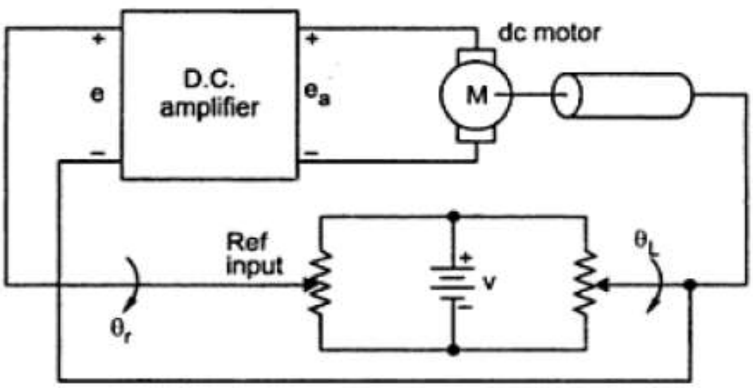
- **Classification/ Types of Servo system:**
  - DC Servo system, AC Servo system
- **Servo Components:**
  - Error Detector: Potentiometer (for DC servo system), Synchro error detector (for AC servo system)
  - Servo amplifier: DC servo amplifier, AC servo amplifier
  - Servo Motor: The types of Servo motors are DC servo motor, AC servo motor and Stepper motor. A servo motor is a rotary actuator that allows precise control of angular position, velocity or acceleration. Servomotors are used in application where instant and accurate positioning of load is required because servo motor has very low inertia.

https://www.youtube.com/watch?v=6-IdwP-YDzI

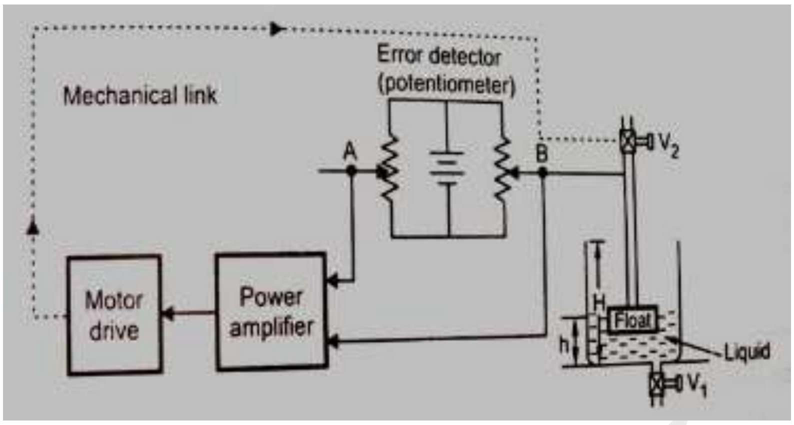
4. DC position control system

- DC position control system consists of DC components such as 2 potentiometers in parallel as error detector, DC servo amplifier and DC servo motor which is connected to the load.
- The load is connected to the wiper of one the potentiometer as feedback.
- The other potentiometer wiper is kept constant at the reference position.
- The differential output of the 2 potentiometers is the error voltage which is given to the servo amplifier.
- The amplifier output which is the error voltage is given to the motor.
- Thus, the speed of the motor is adjusted according to the error voltage and feedback signal.
- Thus, the load is positioned according to the reference signal.

Block diagram of DC position control (DC Servo) system:



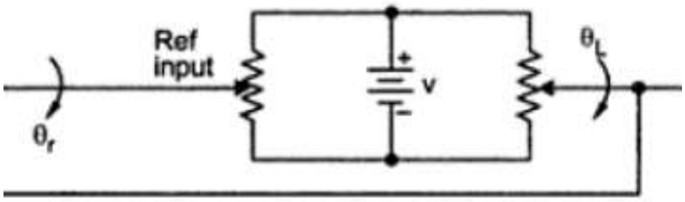
Example for DC position control (DC Servo) system:



- In the level control system given here, level sensor is connected to the wiper of feedback potentiometer. The other potentiometer wiper is kept constant at the reference position.
- The differential output of the 2 potentiometers is the error voltage which is given to the servo amplifier.
- The amplifier output which is the error voltage is given to the motor.
- Thus, the speed of the motor is adjusted according to the error voltage and feedback signal.
- Thus, the control valve position is adjusted according to the reference signal and level is controlled.

5. Potentiometer as error detector

- An assembly of two potentiometers in parallel is used as error detector in DC servo system.

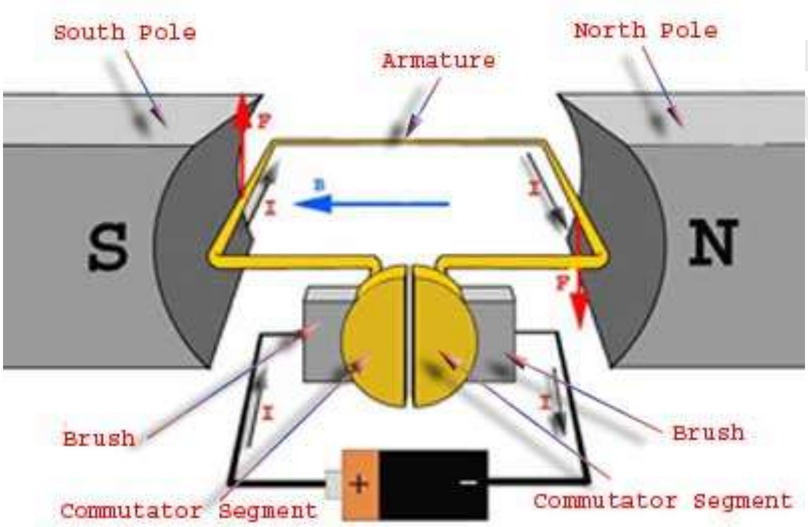


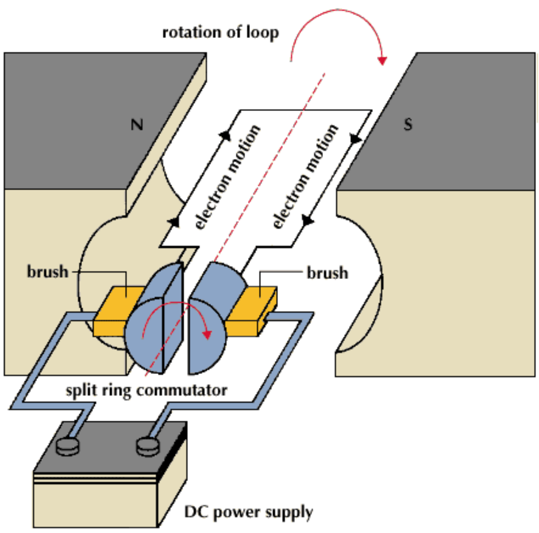
- This type of arrangement allows comparison of two separately located shaft positions.
- The output voltage is taken across the variable terminals of the two potentiometers. It gives the output voltage proportional to the difference in the positions of both the wipers of potentiometers.
  - $e \propto (\theta_r - \theta_L)$
- It is given to servo amplifier.
- The motor, in turn, moves and the shaft connected to the load potentiometer moves with it in such a way as to make the output voltage zero.
- That is, the output (Load) potentiometer shaft moves in accordance with the shaft of the input (reference) potentiometer

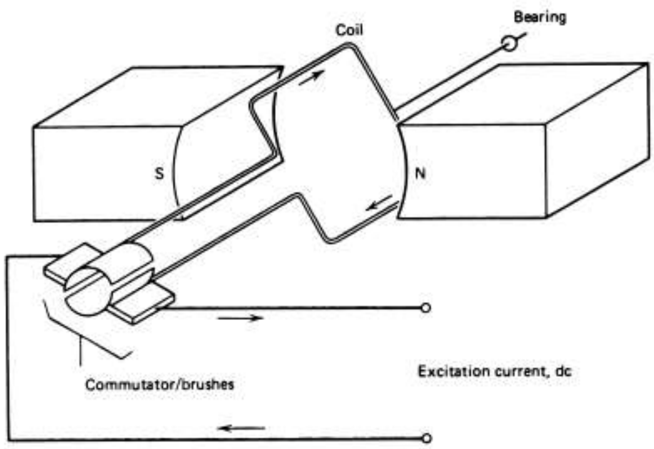
6. DC servo motor construction (revision)

- DC servo motor is similar to DC motor in principle and operation.
- In the DC motor, electrical current is passed through coils that are arranged within a fixed magnetic field. The current generates magnetic fields in the coils; this causes the coil assembly to rotate, as each coil is pushed away from the like pole and pulled toward the unlike pole of the fixed field. To maintain rotation, it is necessary to continually reverse the current—so that coil polarities will continually flip, causing the coils to continue "chasing" the unlike fixed poles.

- DC motors have brushes and commutator; the brushes deliver current through the commutator into the coils on the rotor.
- Power to the coils is supplied through fixed conductive brushes that make contact with a rotating commutator; it is the rotation of the commutator that causes the reversal of the current through the coils.
- As the commutator rotates, it continually flips the direction of the current into the coils, reversing the coil polarities so that the coils maintain rightward rotation. The commutator rotates because it is attached to the rotor (which is called the armature) on which the coils are mounted.



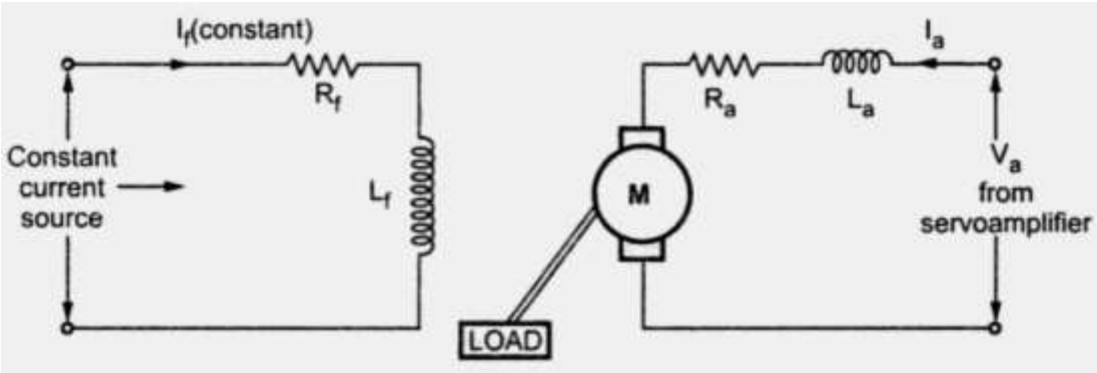




7. Armature controlled D.C. servo motor

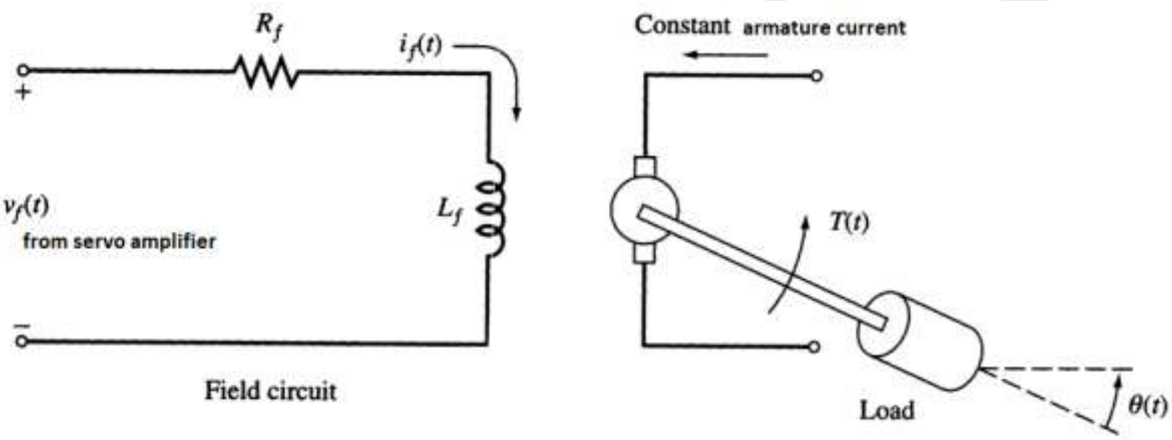
- In an armature-controlled DC servomotor, the control signal available from the servo amplifier is applied to the armature of the motor.
- The field winding is supplied with constant current hence the flux remains constant. So, these motors are also called as constant magnetic flux motors. It is easy to keep field

current constant rather than armature current. This is because presence of back e.m.f. in the armature.



Armature controlled D.C. servo motor

8. Field controlled D.C. servo motor



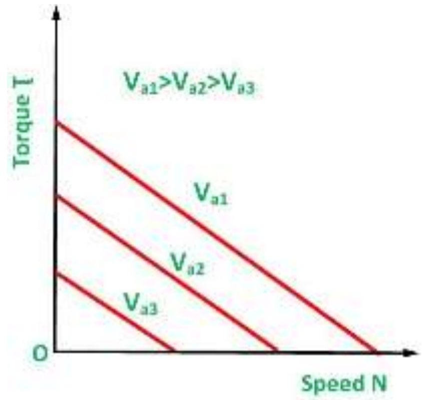
- In a field-controlled DC servomotor, the control signal available from the servo amplifier is applied to the field of the motor.
- The armature winding is supplied with constant current.

9. Comparison of Field-controlled and Armature -controlled DC servomotor

Field-controlled DC servomotor	Armature -controlled DC servomotor
Field is excited by control voltage (from servo amplifier)	Armature is excited by control voltage (from servo amplifier)
Armature current kept constant	Field current kept constant
It is open loop system	It is close loop system
Efficiency is poor	Efficiency is better
Required low power amplifiers	Required high power amplifiers
It has large time constant due to large $\frac{L_f}{R_f}$ ratio	It has small time constant
Cost is low	Cost is high

10. DC servo motor characteristics:

- Torque-speed characteristic of DC servo motor is linear.
- In the following graph, V_a is the armature voltage.

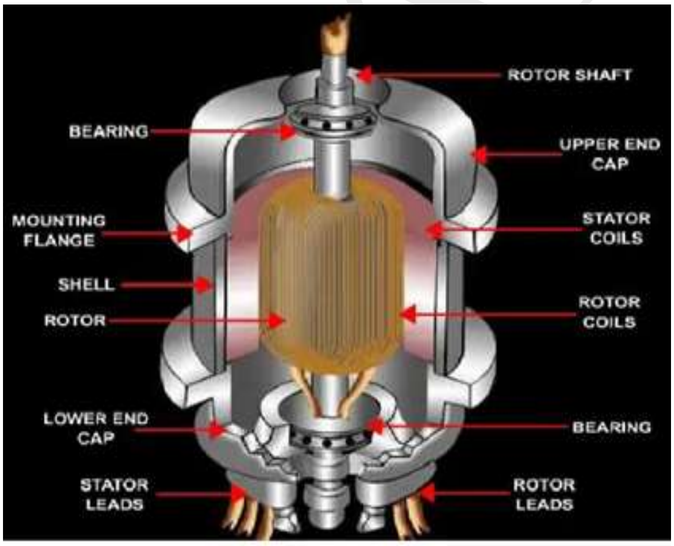


11. Difference of DC servo motor from a normal DC motor

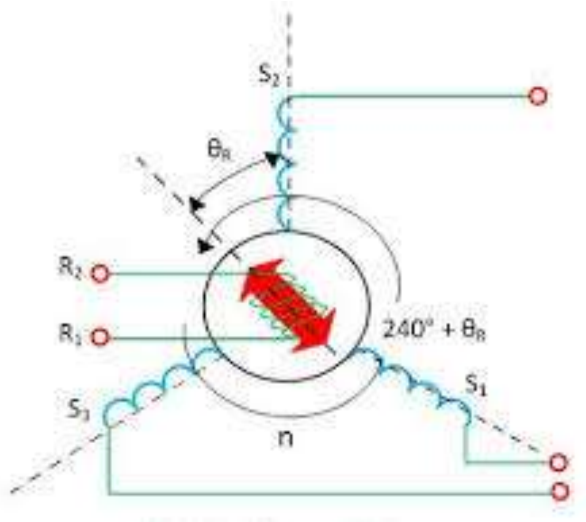
- Servo motor is required to produce rapid acceleration from standstill. Therefore, it should have less inertia and high starting torque. Low inertia is attained by reducing the diameter of the armature and increasing its length. Thus, DC servo motor is similar to ordinary DC motor with minor differences.

12. Synchro as error detector in AC servo system

- Synchro is an electromagnetic transducer converting the angular position into electrical signal. It is an electric system for transmitting angular position or motion.
- Synchro consists of an electromagnetic rotor with winding and three stator windings separated by 120 degrees. It produces an output voltage depending upon the angular position of the rotor.



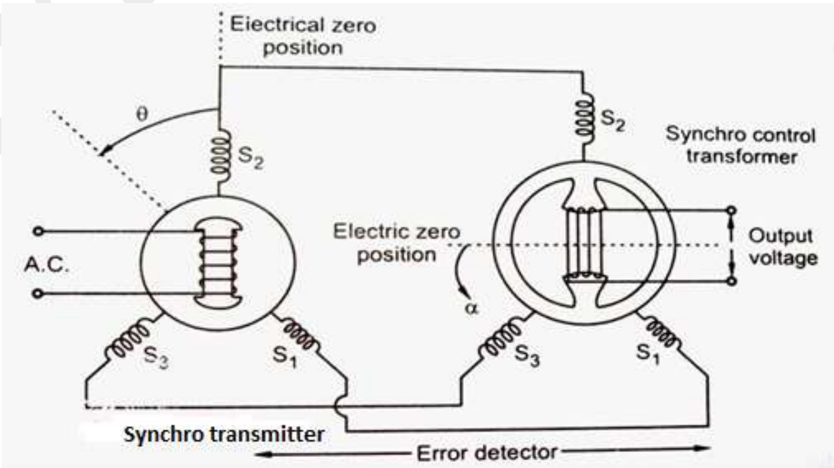
- Synchro transmitter rotor is dumb bell shaped. Therefore, the flux is sinusoidally distributed in the air gap. Synchro transmitter is also known as synchro generator.
- Maximum voltage is induced in a stator winding of synchro transmitter when the rotor and stator winding have 0-degree angle between them. The diagram is given below.



- Synchro transmitter along with synchro control transformer is used as error detector in AC servo system.
- The control transformer is similar in construction to that of synchro transmitter except that its rotor is cylindrical in shape. Therefore, the flux is uniformly distributed in the air gap.
- The voltage induced in the stator coils and corresponding currents of the transmitter are given to the control transformer stator coils. (The output of the synchro transmitter is given to the stator windings of the control transformer as shown.)
- Circulating currents of same phase but different magnitude will flow through both set of stator coils.
- This establishes an identical flux pattern in the air gap of control transformer.
- The flux pattern in the air gap of control transformer will have the same orientation as that of transmitter rotor.
- The voltage induced in the transformer rotor will be proportional to the cosine of angle between the two rotors.
- The output equation is given by:

  $$e(t) = k\, V_r \sin \omega t \, cos\Phi$$

  Where $V_r \sin \omega t$ the input voltage to the transmitter rotor and ϕ is the angular difference between both rotors.
- When ϕ=90 both rotors are perpendicular to each other and the output voltage is zero. This position is called <u>electrical zero</u> and is used as reference position.
- The error voltage is proportional to the angular difference between the shaft positions of transmitter and control transformer.



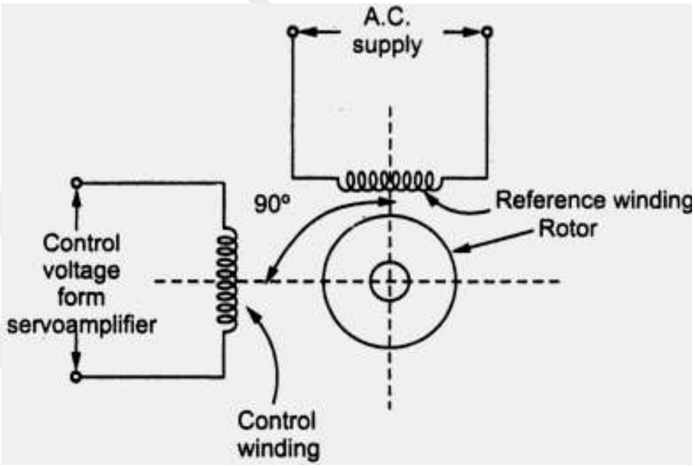
Synchro as error detector

13. Applications of synchro:

- Synchros are used primarily for the rapid and accurate transmission of information between equipment and stations. Examples of such information are changes in course, speed, and range of targets or missiles; angular displacement (position) of the ship's rudder; and changes in the speed and depth of torpedoes.

14. AC servo motor operation with diagram.

- AC servo motor is similar to 2 phase induction motor with minor constructional differences. Servo motor is required to produce rapid acceleration from standstill. Therefore, it should have less inertia and high starting torque.
- Low inertia is attained by reducing the diameter of the rotor and increasing its length. Thus, AC servo motor is similar to normal 2 phase AC motor with minor differences.
- It consists of 2 stator windings known as reference and control windings uniformly distributed and displaced by 90^0 .
- Rotor and stator are made of electromagnetic material.
- The rotor has windings in it which makes short-circuited paths.
- No external voltage is applied to rotor.
- The stator reference winding is excited by a constant AC supply.
- The stator control winding is excited by a variable error voltage which is obtained from servo amplifier.
- This results in magnetic field currents which gives a rotating magnetic field in stator
- When it sweeps over the rotor, voltages are induced in rotor windings.
- This induces magnetizing currents in the rotor winding which in turn generates the interacting magnetic field of the rotor.
- The rotating magnetic field of stator interacts with the magnetic field of the rotor and this produces torque on the rotor which causes the rotor to rotate.
- Diagram of AC motor:

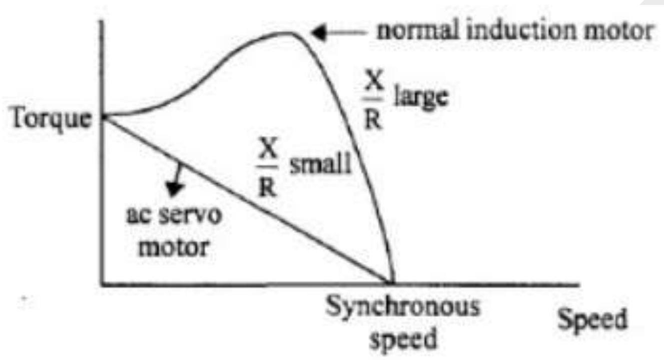


15. Difference between AC servomotors and a normal 2-phase induction motor.

Sr.No	AC servo motor	2 phase induction motor
1	Low inertia	High inertia
2	Linear Torque-speed characteristic	Nonlinear Torque-speed characteristic
3	Less susceptible to low frequency noise	Susceptible to low frequency noise

4	Low power applications	Low and high-power applications
5	Diameter of rotor is small	Diameter of rotor is large
6	X/R ratio is less (rotor resistance is more)	X/R ratio is more
7	Can be used where noise disturbance creates problems	Cannot be used

16. Torque-speed characteristic of AC servomotor & normal 2-phase Induction motor



The characteristics of normal induction motor is nonlinear with initial positive slope. The characteristics of AC servo motor is made linear with negative slope to improve the stability since it is used in servosystem which is a feedback system. This is achieved by small ratio of $\frac{X}{R}$ which is obtained by increasing the resistance of the rotor winding. (The speed is reduced by increasing the resistance of the rotor winding). The increase in rotor resistance may cause heat dissipation and power loss. Therefore, AC servomotor is not preferred for high power applications.

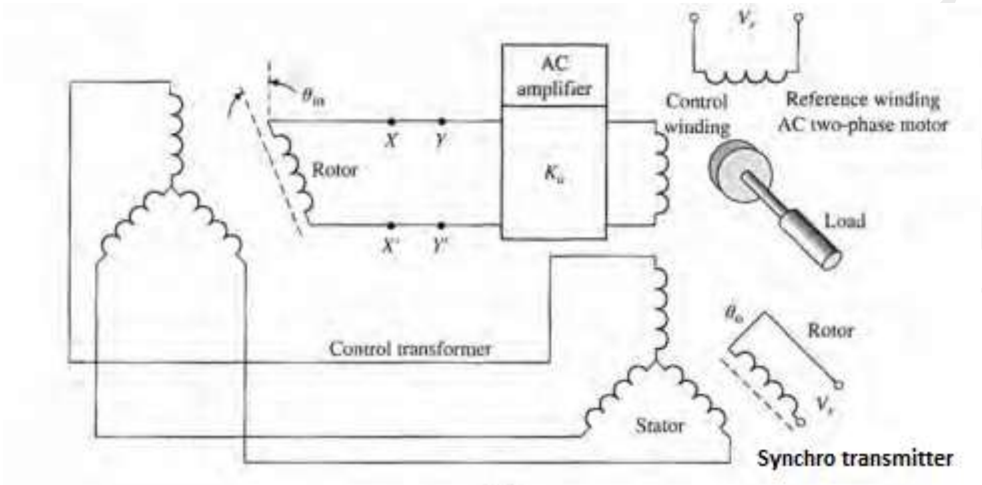
17. Comparison of AC servomotor with DC servomotor

AC servomotor	DC servo motor
Control winding is present	Control winding is absent
Supply/Control voltage is applied to stator	Supply/Control voltage is applied to armature
Brushes and commutators are not present	Brushes and commutators are present
No RF noise	RF noise is present
Less maintenance	More maintenance
Nonlinear response	Linear response
Low power application	High power application
Poor efficiency	Better efficiency
Economical, less costly	Costly
Application: Computer peripherals, recorders, aircrafts	Application: Machine tools, robotics

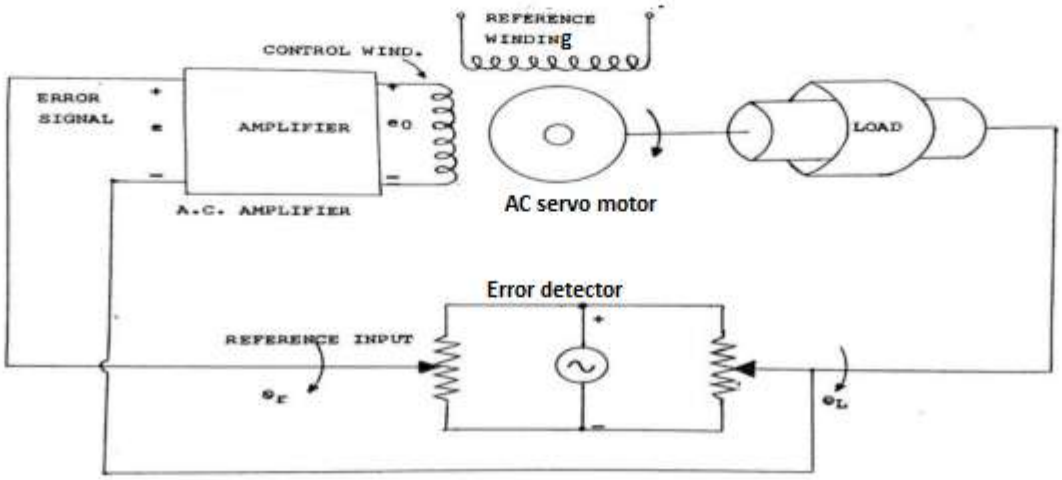
18. AC Servo system:

- AC position control system consists of AC components such as Synchro as error detector, AC servo amplifier and AC servo motor which is connected to the load.
- The load is connected to the rotor of synchro transmitter as feedback.

- The rotor of synchro control transformer is kept constant at the reference position.
- The differential output of the synchro error detector is the error voltage which is given to the AC servo amplifier.
- The amplifier output which is the error voltage is given to the control winding of AC servo motor.
- Thus, the speed of the motor is adjusted according to the error voltage and feedback signal.
- Thus, the load is positioned according to the reference signal.



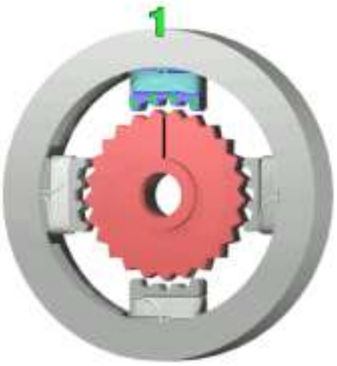
Or,



19. Stepper motor:

- It is an electromechanical device which moves in steps in response to input pulses.
- It can be interfaced with digital circuits easily.
- It completes a full rotation by sequencing through a series of discrete rotational steps.
- Each step position is an equilibrium position in that, without further excitation, the rotor position will stay at the latest step.
- Thus, continuous rotation is achieved by the input of a train of pulses, each of which causes an advance of one step. It is not really continuous rotation, but discrete, stepwise rotation.

- The rotational rate is determined by the number of steps per revolution and the rate at which the pulses are applied.
- A driver circuit is necessary to convert the pulse train into proper driving signals for the motor
- It consists of stator and rotor.
- The stator is cylindrical with poles or teeth. Each pole has coils or windings to which the input pulses are applied. The stator poles are always taken as north and south poles which are opposite to each other in arrangement. A combination of two stator poles (one north and one south pole) makes 1 stator phase. Excitation of stator poles makes them North Pole.
- In rotor, one north-south combination together is taken as one pole.
- Step angle is the angular displacement of the rotor of stepper motor for one pulse input.
- Applications: computer peripherals, robotics, digital applications, printers



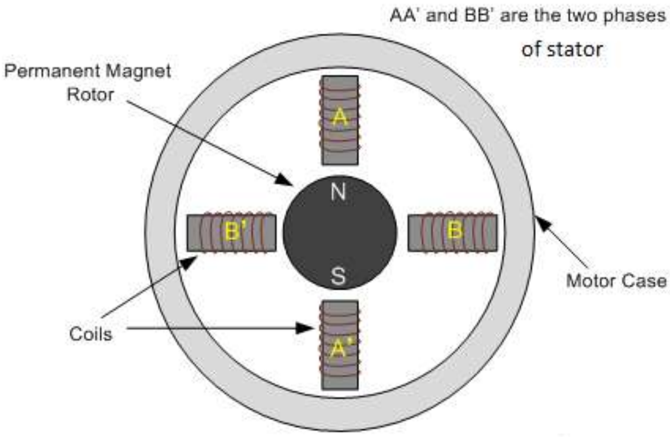
https://en.wikipedia.org/wiki/Stepper_motor#/media/File:StepperMotor.gif

20. Types of stepper motor (based on rotor):

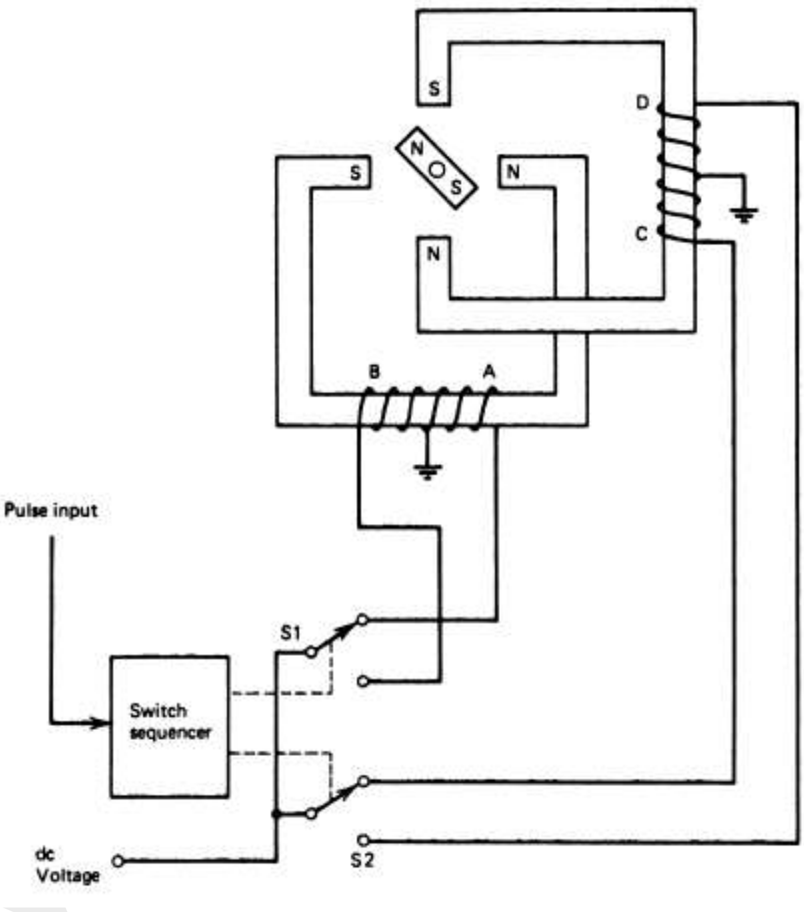
1. Permanent magnet stepper motor
2. Variable reluctance stepper motor
3. Hybrid stepper motor (combination of Variable reluctance and permanent magnet stepper motor).

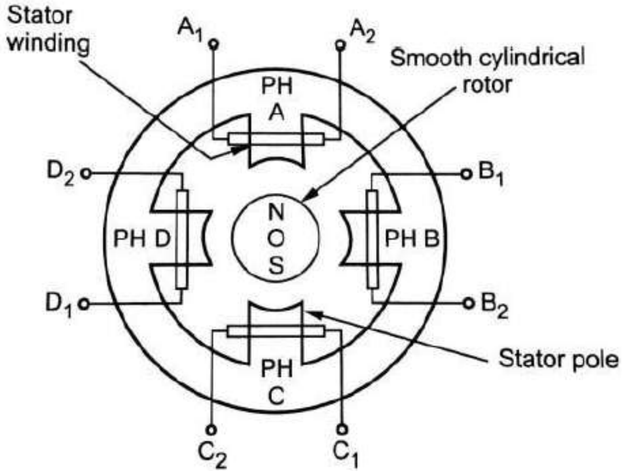
21. Permanent magnet stepper motor

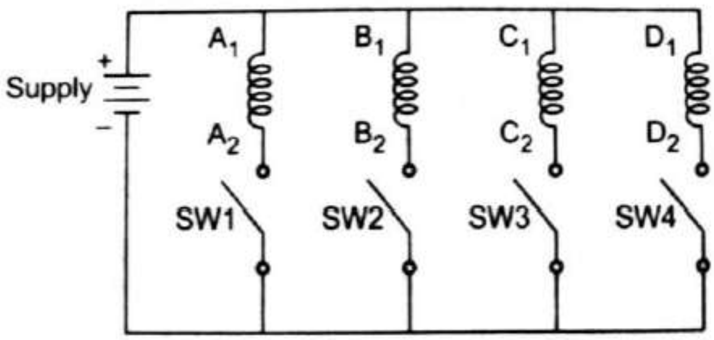
- Here, the rotor is made up of permanent magnet.
- They are repelled or attracted towards the stator according to pulses applied. This type gives large step angle.



Two-Phase Permanent Magnet type Stepper







- The stator of this type of stepper motor has four poles. Around the poles exciting coils are wounded (A, B, C, D)
- Rotor is smooth cylindrical type. It is made up of ferrite material and permanently magnetized.

Working:

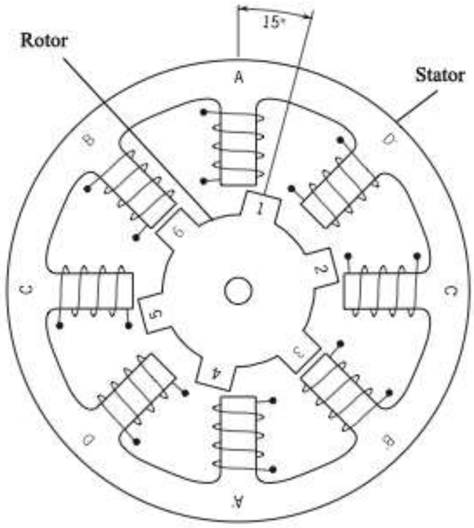
- When voltage pulses are applied to various phases with the help of driving circuit, the rotor makes 90^o revolution called step for each input voltage pulse
- It can be explained as:
- When switch SW1 is closed exciting the phase A, we have a North Pole in phase A due to this excitation. An electromechanical torque is developed and rotor rotates to adjust its magnetic axis with the magnetic axis of the stator.
- Next phase B is excited with switch SW2 after disconnecting phase A. Due to this, rotor further rotates to adjust its magnetic axis with north pole of phase B.
- Hence it rotates through 90^o step angle.
- Similarly, when phase C and phase D are sequentially excited, the rotor tends to rotate through 90^o in clockwise direction, every time when such sequence is repeated.

22. Variable reluctance stepper motor:

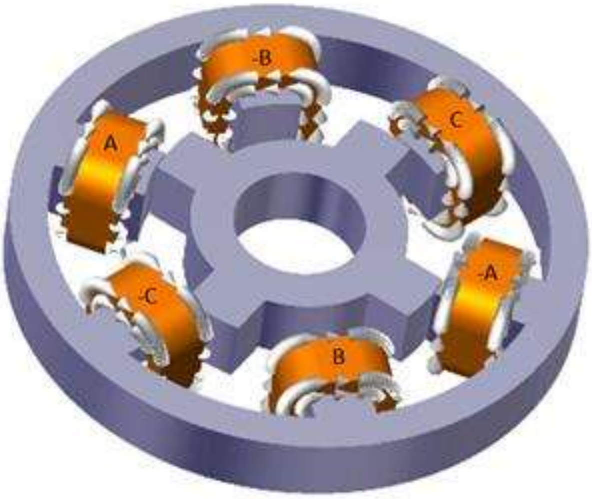
- They have iron core rotor which is attracted towards the stator poles and provide movement by minimum reluctance between stator and rotor.
- Here, the rotor is made up of magnetic material with a certain number of teeth. This type gives small step angle. The rotor is driven by a phased arrangement of stator coils (i.e north and south poles) with different number of poles so that the rotor cannot be in perfect alignment with stator.
- Variable reluctance stepper motor is based on the principle that minimum reluctance occurs with minimum gap.
- Step angle can be reduced by increasing the number of rotor and stator poles.

23. Variable reluctance stepper motor with 4 phase stator (8 stator poles) and six teeth rotor:

- The coils on the stator are arranged in terms of coil pairs, like A and A' forms a pair, B and B' forms a pair and so on. So, each of this coil pair form an electromagnet and they can be energised individually using a driver circuitry.
- When a coil gets energised it acts as a magnet and the rotor pole gets aligned to it.
- When the rotor rotates to adjust itself to align with the stator it is called as one step**.** Similarly, by energising the coils in a sequence, the motor can be rotated in small steps to make a complete rotation.



24. Variable reluctance stepper motor with 4 phase stator (8 stator poles) and 4 teeth rotor:



25. Variable reluctance stepper motor with 3 phase stator (6 stator poles) and two teeth rotor:

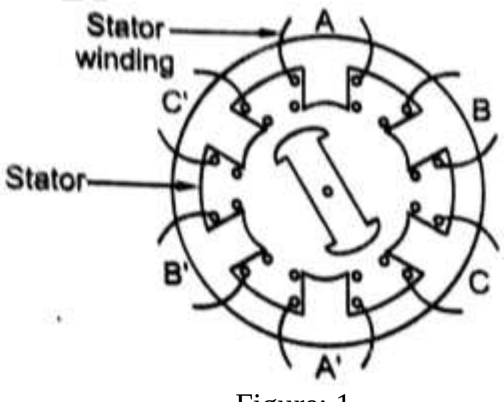


Figure: 1

- The stator in the given stepper motor is wound for three phases. It has six salient poles (teeth) with concentrated exciting windings around each one of them.

- The rotor is made out of slotted steel laminations and has two salient poles (or teeth) without any exciting windings as shown in the figure 1. The basic drive circuit is shown in fig.2.

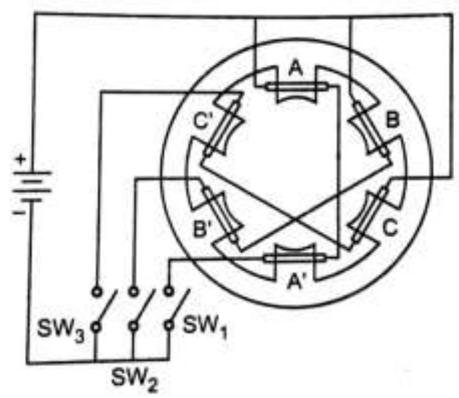


Figure:2

Explanation:

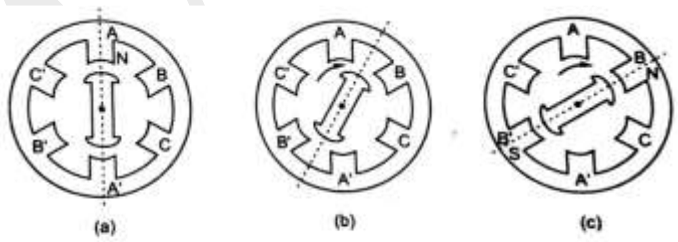
- The coils wound around diametrically opposite poles are connected in series and the three phases are energized from a DC source with the help of switches.

i) When the phase A-A’ is excited with switch SW1 closed with A forming N Pole and A’ as S Pole, the rotor tries to adjust itself in a minimum reluctance position between stator and rotor as shown in the fig.a.

ii) When the phase B-B’ is also excited with switch SW2 closed, keeping A-A’ energized the magnetic axis of stator moves 30^0 in clockwise direction and hence rotor also rotates through 30^0 steps in clockwise direction to attain new minimum reluctance position as shown in fig.b.

iii) After that the excitation of AA’ is disconnected and only BB’ is kept energized. Rotor further moves through 30^o step to adjust itself in new minimum reluctance position as shown in fig.c.

iv) By successively exciting three phases in the specific sequence, the motor takes twelve steps to make one complete revolution.

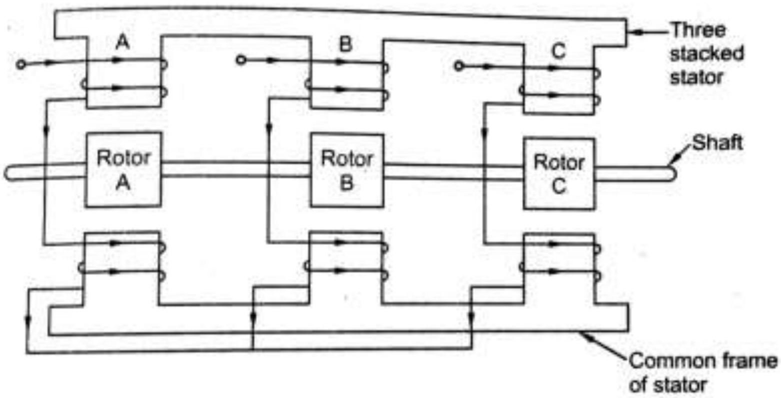


26. Multi-stack variable reluctance stepper motor:

- In this type, the windings are arranged in different stacks.
- The figure represents a three-stack stepper motor.
- The three stacks of the stator have a common frame. The rotors have a common shaft.
- The stator stacks and rotors have toothed structure with same teeth size.
- The stators are pulse excited and rotors are unexcited. When the stator is excited, the rotor gets pulled to the nearest minimum reluctance position where the stator and rotor teeth are aligned.

- The stator teeth of various stacks are arranged to have a progressive angular displacement of :

  $\alpha = 360^0/(q*T)$ where q = number of stacks, T = number of teeth .



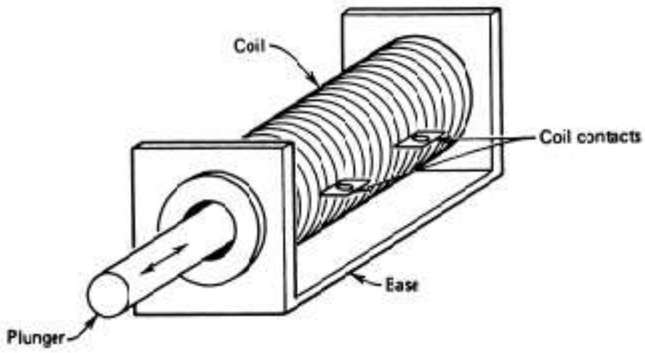
YouTube link:
https://www.youtube.com/watch?v=VfqYN1eG9Zk

27. Comparison of stepper Motor with DC Servo Motor.

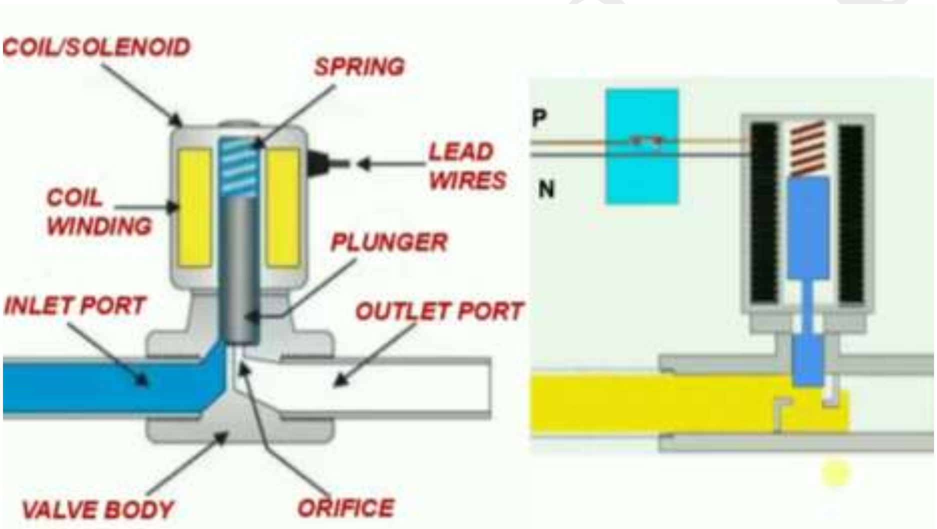
Sr.no	Stepper Motor	DC Servo Motor
1	It gives stepwise rotation	It gives continuous rotation
2	Steps are controlled by number of pulses	Rotation is controlled by input voltage
3	Supply voltage is given to stator	Supply voltage is given to rotor
4	It is brushless	It has brushes and commutator
5	Due to absence of brushes no wear and tear. Hence less maintenance	Maintenance is required.
6	Speed is governed by frequency of switching	Speed is controlled by supply voltage
7	Applications: computer printers, image scanners, CD drives, camera lenses, CNC machines and 3D printers.	Robotics, Machine Tool (Metal Cutting), Antenna Positioning, Printer, Automation

28. Principle and working of Solenoid Actuators

- A solenoid is an electromagnetic actuator that converts electrical energy into mechanical action
- Solenoids are used when a large, sudden force must be applied to perform certain job.
- The solenoid consists of an electric coil and a ferromagnetic plunger. The coil is tightly wrapped around an iron core. The electric coil is positioned around the plunger.
- As soon as an electrical current passes through the coil when excited by the specified voltage, a magnetic field is generated around the coil. It generates an electromagnetic force which pulls the plunger up towards the centre of the coil.
- The electromagnetic force generated can be increased using two ways. The first is by adding more loops or windings in the coil. This increases the number of magnetic field lines or flux emanating from the coil. The second method is by increasing the amount of current flowing through the coil. This increases the supply voltage into the solenoid.



- The main part of a pneumatic solenoid valve is the solenoid. Solenoids valves operate with either DC or AC voltages.
- In the solenoid valve an electric coil is positioned around the plunger. As soon as the coil is electrically energised a magnetic field is created which pulls the plunger up towards the centre of the coil. This opens the orifice so that the medium can flow through it.



29. Principle and working of Brushless DC (BLDC) motor

- Brushless DC motors do not use brushes.
- The rotor is a permanent magnet; therefore, it does not have coils.
- The stator consists of the coils. Since the stator is stationary, the coils do not move and therefore, there is no need for brushes and commutator. Current to the fixed coils is controlled from the outside.
- Rotation of the rotor is achieved by changing the direction of the magnetic fields generated by the surrounding stationary coils. To control the rotation, the magnitude and direction of the current into these coils should be adjusted.
- A BLDC motor with three coils on the stator will have six electrical wires (two to each coil) extending from these coils. In most implementations three of these wires will be connected internally, with the three remaining wires extending from the motor body (in contrast to the two wires extending from the brushed DC motor).

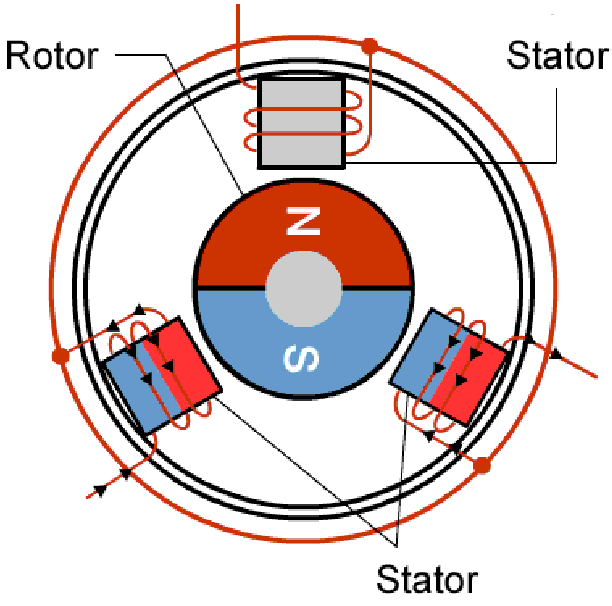


Figure: BLDC Motor

30. Advantages for BLDC Motors

Brushless DC motors (BLDC) have high efficiency, high durability (long operating life), more power output, excellent controllability, low electric noise generation and power-saving advantages.

31. Applications for BLDC Motors

- Because of their efficiency and longevity, they are widely used in devices that run continuously. So they are used in washing machines, vacuum machines, air conditioners, fans, hard disc drives and other consumer electronics.
- They are used to drive service robots
- BLDC motors are also ideal for drones because of their ability to deliver precision control.

32. Comparison of BLDC motor with DC servomotor

BLDC motor	DC servo motor
Supply/Control voltage is applied to stator	Supply/Control voltage is applied to armature
Brushes and commutators are not present	Brushes and commutators are present
Low electric noise	RF noise is present
Less maintenance	More maintenance
High durability	Less durability
High efficiency	Less efficiency
Excellent controllability	Less controllability
More power output than DC motor	Less power output
Application: washing machines, air conditioners, consumer electronics, vacuum machines, fan, hard disc drives, drones, service robot, golf carts	Application: Machine tools, robotics