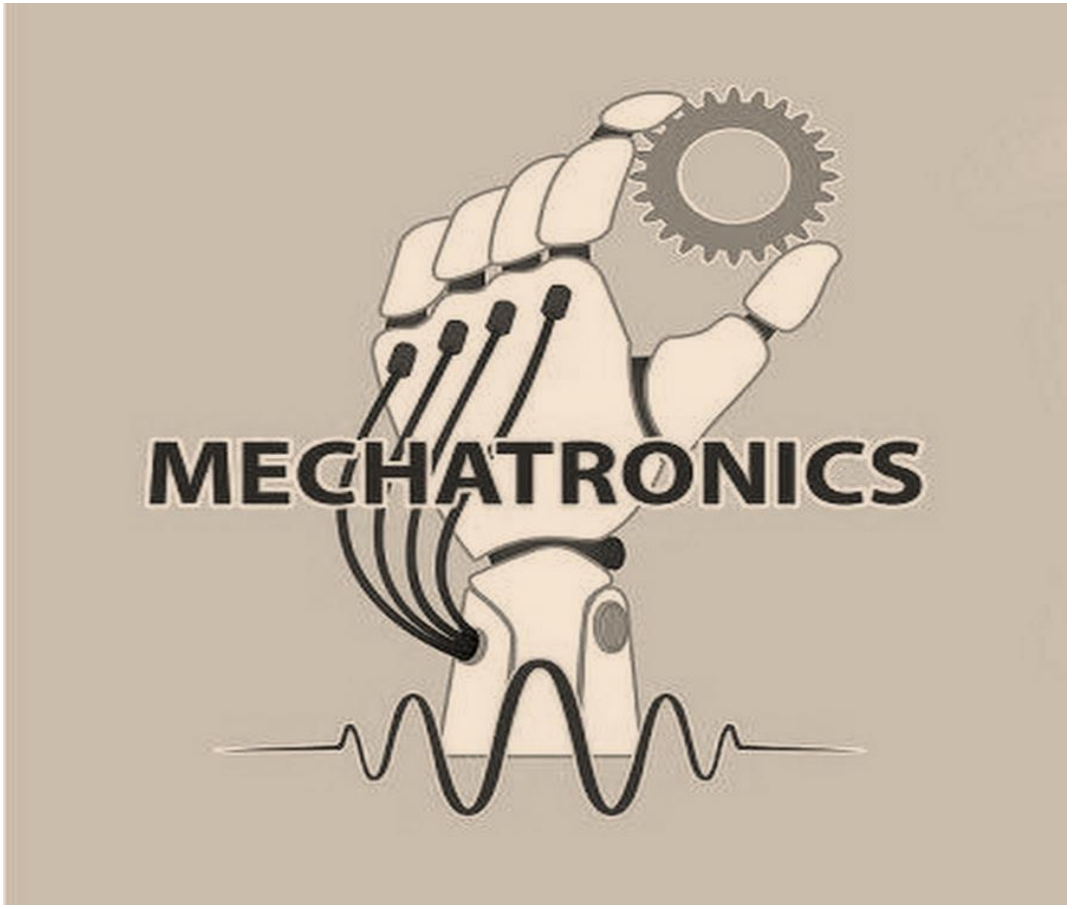

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Mechatronics systems and applications
Code- ARA 204

Syllabus

S. No.	Contents
1	**Introduction**: Definition of mechatronics, measurement system, control systems, microprocessor based controllers, mechatronics approach.
2	**Sensors and Transducers**: Sensors and transducers, performance terminology, photoelectric transducers, flow transducers, optical sensors and transducers, semiconductor lasers, selection of sensors, mechanical / electrical switches, inputting data by switches.
3	**Actuators**: Actuation systems, pneumatic and hydraulic systems, process control valves, rotary actuators, mechanical actuation systems, electrical actuation systems.
4	**Signal Conditioning**: Signal conditioning, filtering digital signal, multiplexers, data acquisition, digital signal processing, pulse modulation, data presentation systems.
5	**Microprocessors and Microcontrollers**: Microcomputer structure, microcontrollers, applications, programmable logic controllers.
6	**Modeling and System Response**: Mathematical models, bond graph models, mechanical, electrical, hydraulic and thermal systems, dynamic response of systems, transfer function and frequency response, closed loop controllers.
7	**Design and Mechatronics**: Input/output systems, computer based modular design, system validation, remote monitoring and control, designing, possible design solutions, detailed case studies of mechatronic systems used in photocopier, automobile, robots.

Unit I **[12]**

Introduction: Introduction to Mechatronics System, Elements of mechatronics system, mechatronics in manufacturing, product and design, Measurement Systems, Control System, comparison between traditional and mechatronics approach.

Sensors and Transducers: Introduction, Performance terminology, static and dynamic characteristics of transducers, Displacement Measurement: Transducers for displacement, displacement measurement, potentiometer, LVDT. Strain Measurement: Theory of Strain Gauges, Bridge circuit, Strain gauge based load cells and torque sensors, Velocity and Motion: Electromagnetic tachometer, photoelectric tachometer, variable reluctance tachometer, Digital Encoders. Vibration and acceleration: Eddy current type, piezoelectric type; Accelerometer: Principle of working, practical accelerometers, strain gauge based and piezoelectric accelerometers. Pressure Measurement: Elastic pressure transducers viz. Bourdon tubes, diaphragm, bellows and piezoelectric pressure sensors. Flow Measurement: Bernoulli flowmeter, Ultrasonic flowmeter, Magnetic flow meter, Rotameter. Miscellaneous Sensors: Leak detector, Flame detector, Smoke detector, pH sensors, Conductivity sensors, Humidity sensors, Potentiometric Biosensors and Proximity sensors. Selection of sensors

Unit II **[10]**

Mechanical Actuation System: Cams, Gear trains, Ratchet and Pawl, Belt and chain drives, Bearings.

Hydraulic and Pneumatic Actuation System: Introduction to Hydraulic and Pneumatic Systems, Directional Control valves, Flow control valves.

Electrical Actuation System: Electrical systems, Solid State Switches, Solenoids, D.C. motors, A.C. motors, Stepper motors.

Unit III **[12]**

Microprocessors: Microprocessor systems, Microcontrollers, applications.

Programmable logic controllers: Programmable logic controllers (PLC) Structure, Input / Output Processing, principles of operation, PLC versus computer, Programming Languages, programming using Ladder Diagrams, Logic Functions, Latching, Sequencing, Timers, Internal Relays And Counters, Shift Registers, Master and Jump Controls, Jumps, Data Movement, Code Conversion, Data handling and manipulation, selecting a PLC.

Unit IV **[8]**

System Models: Mathematical models, Mechanical, Electrical, hydraulic and Thermal Systems, Modelling of dynamic systems.

Design of Mechatronics systems: Stages in designing mechatronics system, Traditional and Mechatronic design.

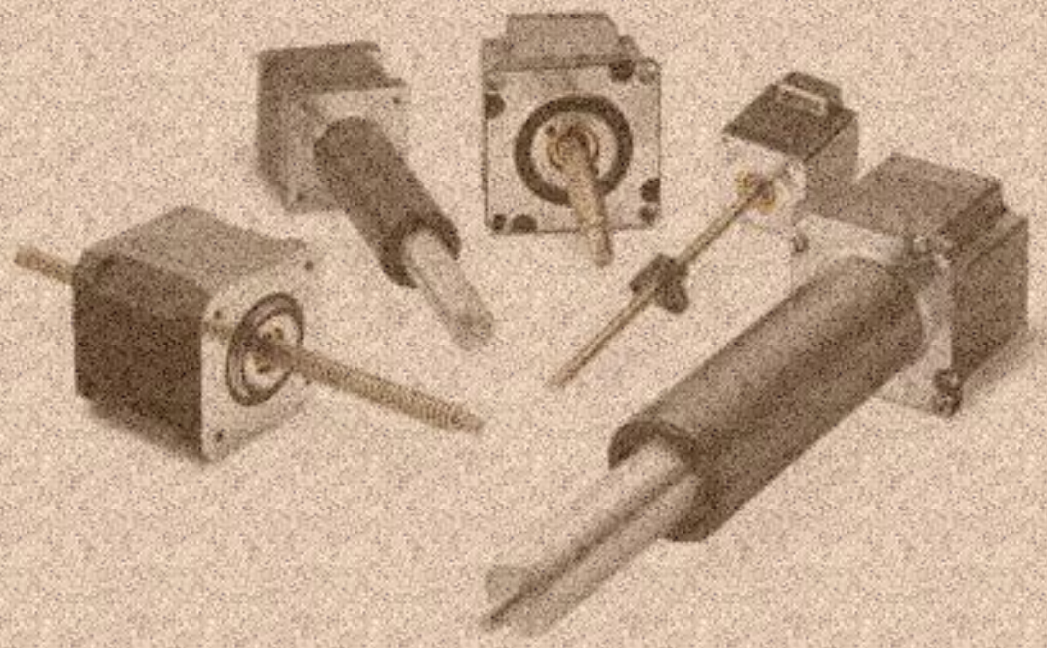
Case studies of Mechatronics system: Mechatronic approach to design, Boat Auto pilot, Pick and place robots, high speed tilting train, automatic car park system, coin counter, engine management system, automated guided vehicle, autonomous mobile system, antilock brake system control, Auto-Focus Camera, Printer, Domestic Washing Machine, Optical Mark Reader, Bar Code Reader

Books

- Mechatronics: Bolton, W., Longman
- Introduction to Mechatronics: D.G. Alciatore & Michael B. Histand; Tata Mc Graw Hill
- Mechatronic system Design; Shetty Dedas, Kolk and Richard
- Mechatronic handbook: Bishop; CRC press
- Intelligent Mechatronic Systems: Modeling, Control and Diagnosis, R. Merzouki, A. K. Samantaray, P. M. Pathak, B. Ould Bouamama, Springer, London

Actuators

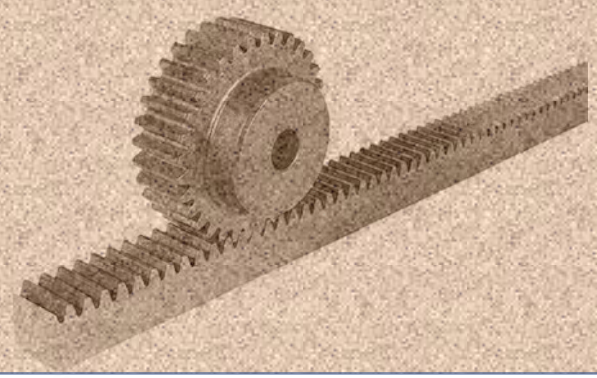
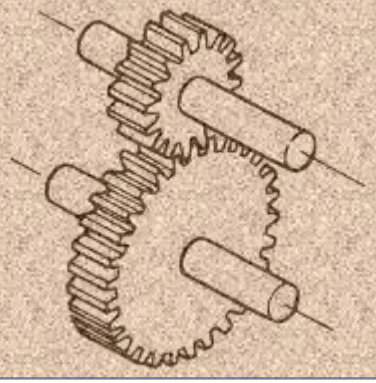
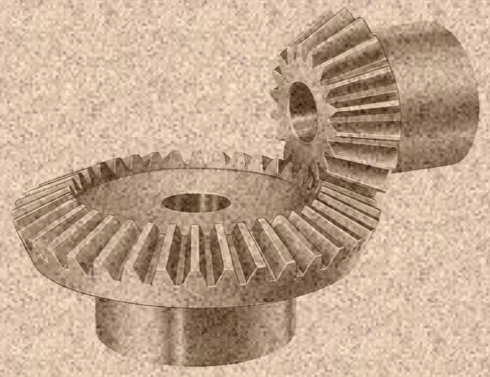
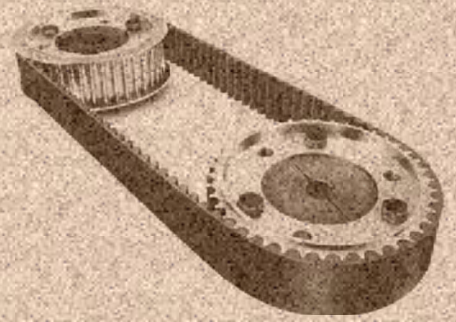
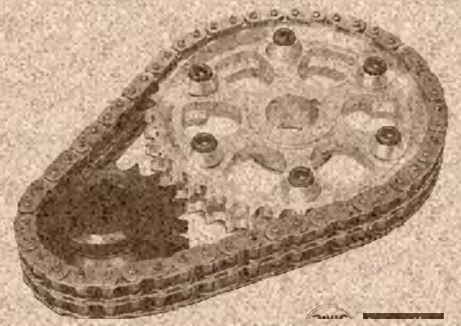
- An actuator is a device that produces a motion by converting energy and signals going into the system. The motion it produces can be either rotary or linear.



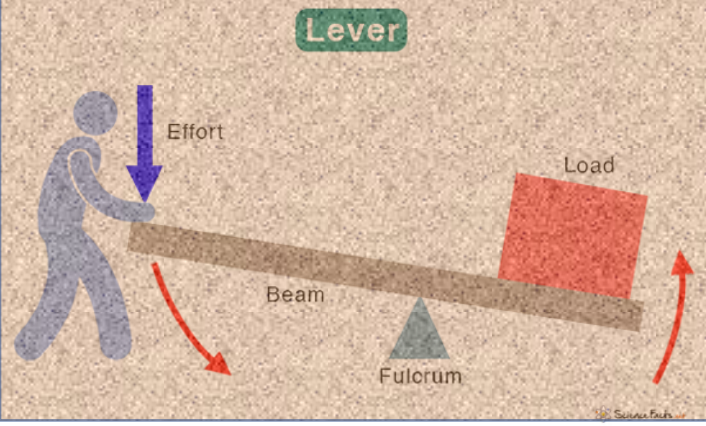
- Elements of control systems responsible for transforming the output of microprocessor or control system into a controlling action on a machine or device.
- Example: Electrical output of controller has to be transformed into linear motion to move a load or do some control action as operating a valve.

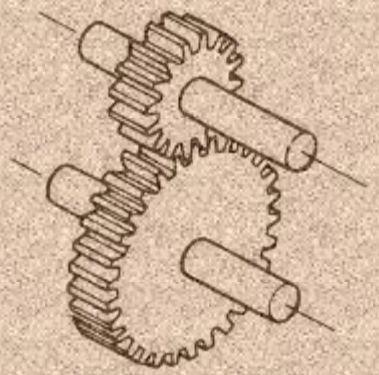
Mechanical Actuation Systems

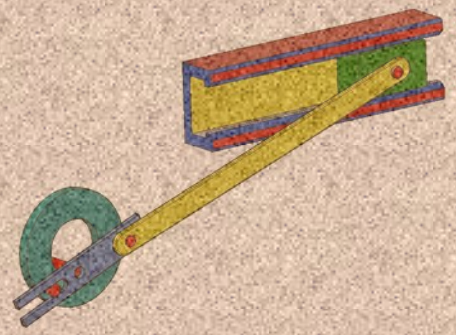
- Mechanism are devices to convert motion from one form to another.
  - Linear to rotary
- They use linkages, cams, gears, rack & pinion, chain, belt drives etc.
  - Rack & pinion – rotational motion to linear motion.
  - Parallel shaft gears – reduce shaft speed.
  - Bevel gears – transmission of rotary motion through 90°.
  - Toothed belt or chain – transmission of rotary motion from one axis to another.

- Many tasks previously done by mechanically are replaced by microprocessors.
- Mechanisms are still used in following functions:
  - Force amplification – Lever.
  - Change of speed – Gear.
  - Transfer of motion from one axis to another – Timing belt.
  - Particular type of motion – Quick return motion.
- Kinematic – Study of motions without regard to forces.

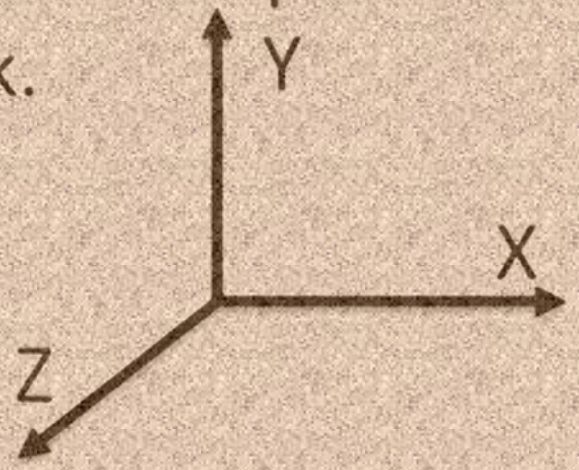




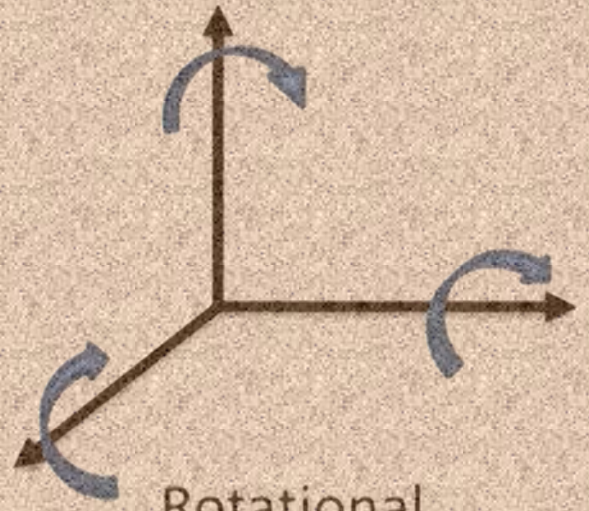


Types of Motion

- Rigid body motion: combination of translational and rotational motion.
- Any motion can be broken down into a combination of translational and rotational motion.
- Such an approach is important when we instruct a robot to do a particular task.



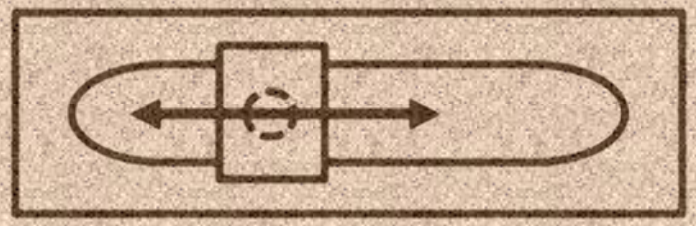
Translational



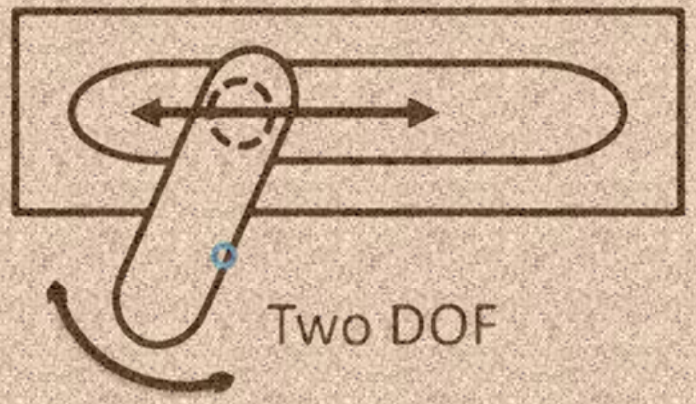
Rotational

Freedom and Constraints

- Degree Of Freedom(DOF) – No. of independent co-ordinates required to specify the motion.
- A body free in space has 6DOF:
  - 3 Translational DOF.
  - 3 Rotational DOF.



One DOF



Two DOF

- Constraints are required to reduce the DOF.
- If we do not have redundant constraint then:

  No. of DOF = 6 – No. of constraints.
- However constraints do occur so, for constraints on a single rigid body the basic rule is:

  6 – No. of constraints = No. of DOF – No. of redundancies.

Kinematic Chains

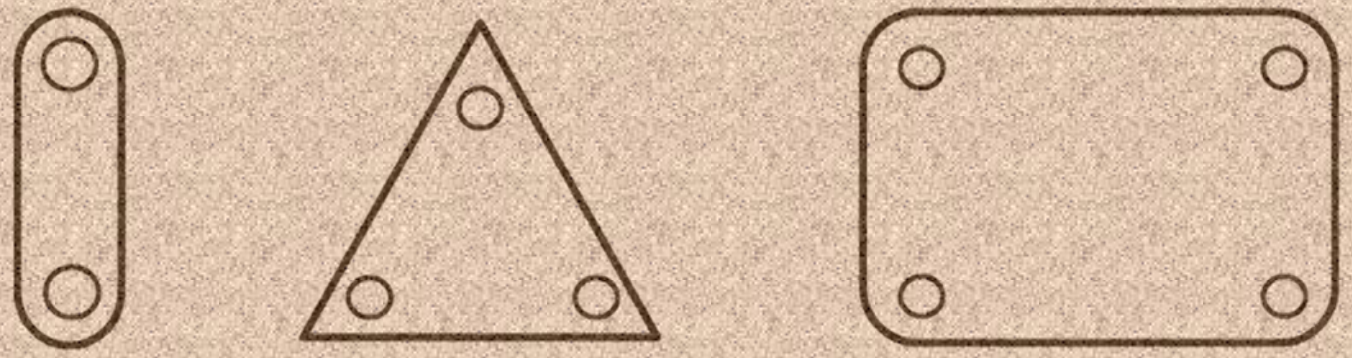
- Each part of a mechanism which has motion relative to some other part is termed as Link.
- A link need not be a rigid body but it must be a resistant body which is capable of transmitting required force with negligible deformation.

Link Examples: Levers, Crank, Connecting rod, Piston, Slider, Pulley, Belts, Shafts etc.

Belt(flexible link)

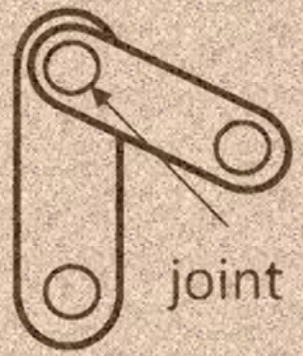
Connecting rod(rigid link)

- Based on number of nodes for connection, types of links:



Binary link Ternary link Quaternary link

- Joint: It is connection between two or more links at their nodes and which allow some motion between the connected links.

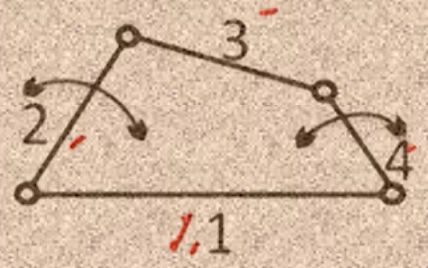


Kinematic Chain

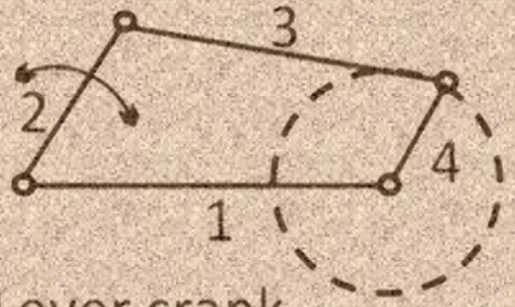
- Sequence of joints and links are called kinematic chains.
- For kinematic chain to transmit motion one link is to be fixed.
- Design of most of the mechanisms are based on two basic forms of kinematic chains:
  1. Four bar chain
  2. Slider crank chain

- Four bar chain:-
  - If sum of the length of shortest link and longest link ≤ sum of length of other two links:
    - Then one link will be capable of making a full revolution w.r.t. fixed link.
  - If this condition is not met:
    - Then none of the link is capable of complete revolution.

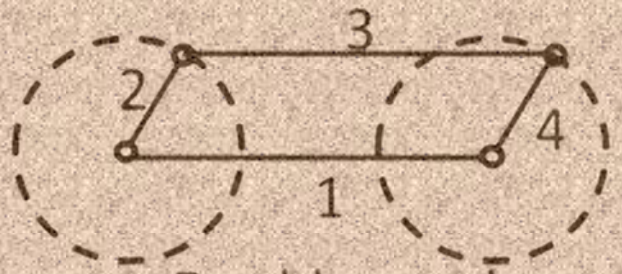
This is called GRASHOF CONDITION.



Double lever mechanism



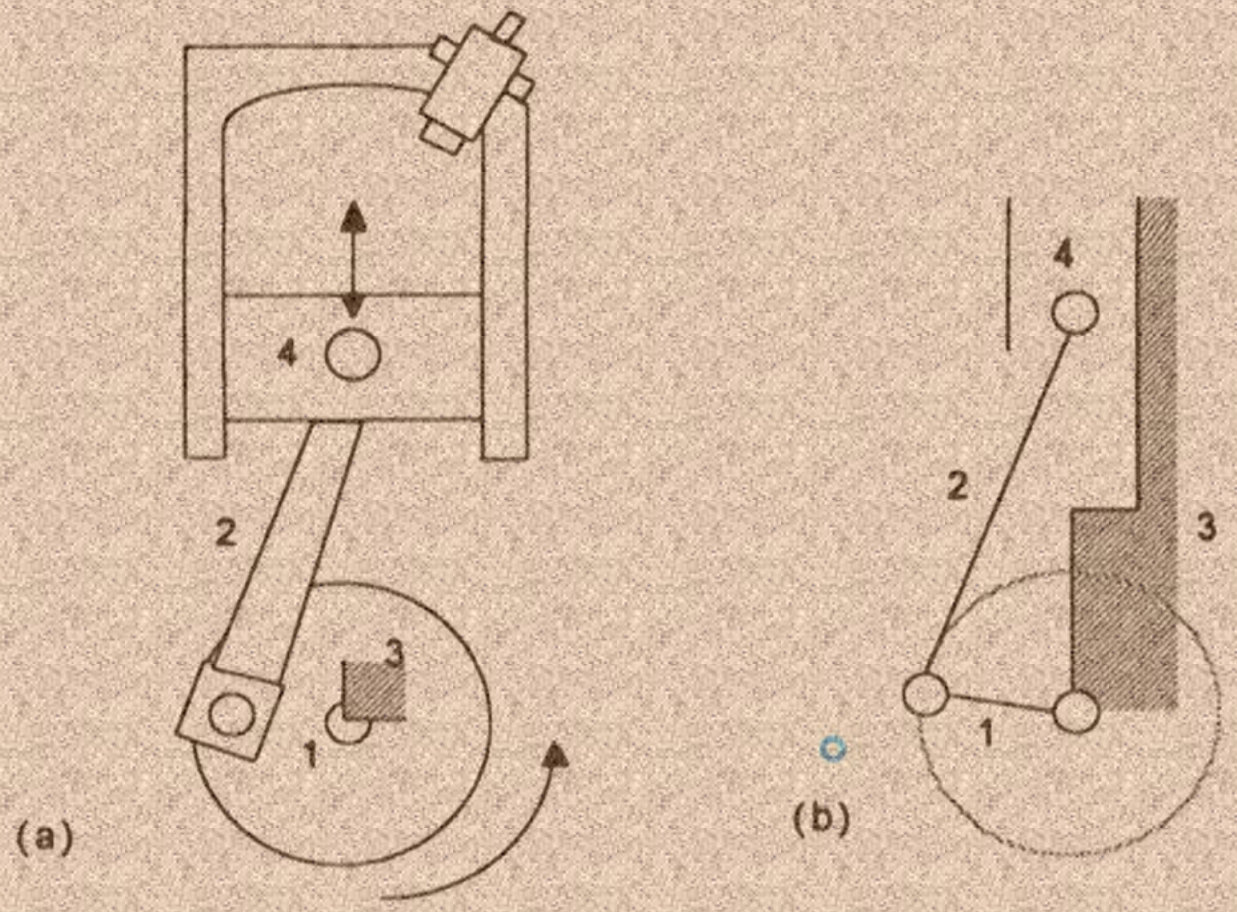
Lever crank mechanism



Double crank mechanism

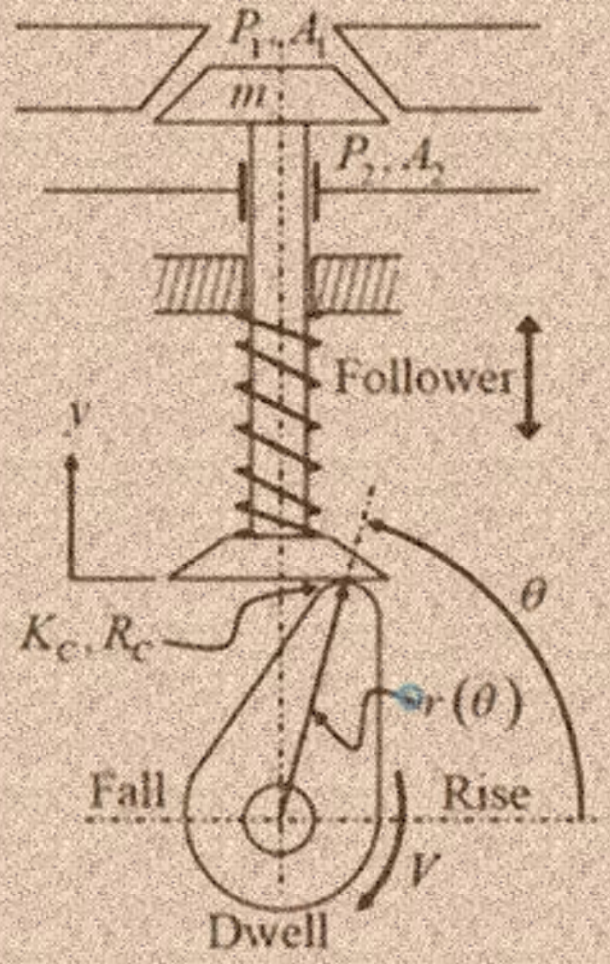
The slider–crank mechanism

- This form of mechanism consists of a crank, a connecting rod and a slider.
- The mechanism transforms an input of backwards and forwards motion into rotational motion



Cam & Cam Follower

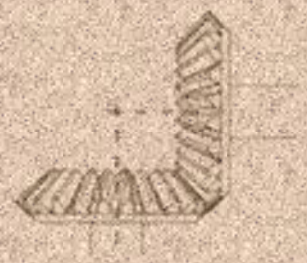
- A cam is a body which rotates or oscillates and in doing so imparts a reciprocating or oscillatory motion to a second body, called the follower, with which it is in contact.
- As the cam rotates so the follower is made to rise, dwell and fall; the lengths of times spent at each of these positions depending on the shape of the cam.



Gear Trains

- To transfer and transform rotary motions.
  - Gear axes:

Parallel axis



Intersecting axis

Rack and pinion

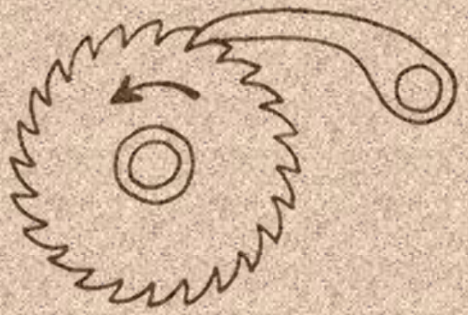
  - Gear type:

Spur

Helical

Double helical

- Ratchet and Pawl:-
  - Lock a mechanism when holding a load.



Pawl

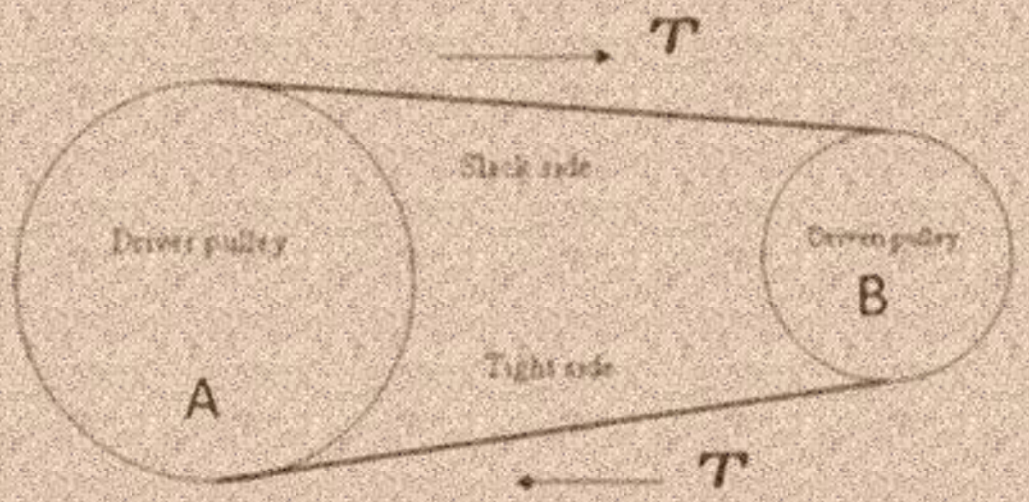
Ratchet wheel

- Belt and Chain Drives:-

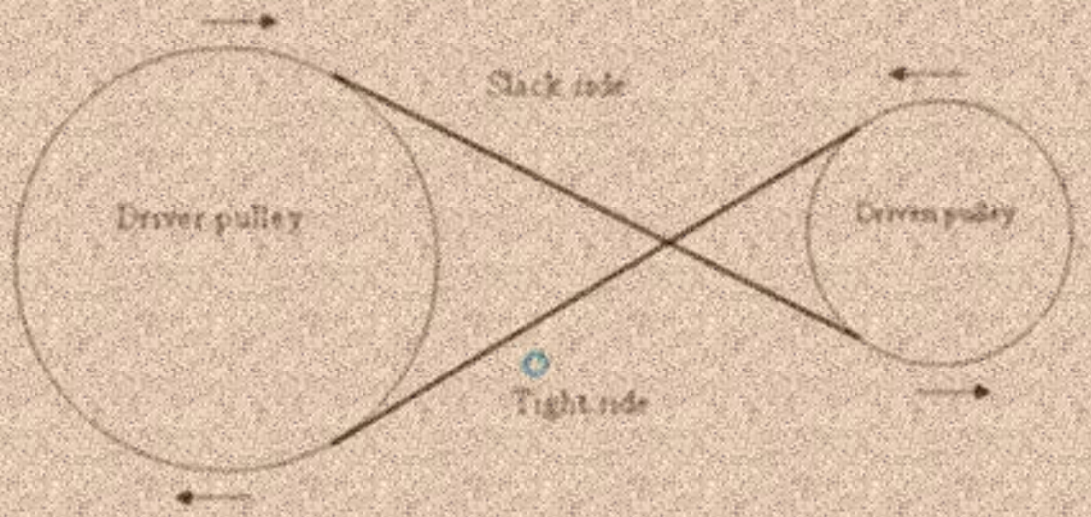
Torque on A = $(T_1 - T_2)r_A$

Torque on B = $(T_1 - T_2)r_B$

Power = $(T_1 - T_2)V$



Open belt



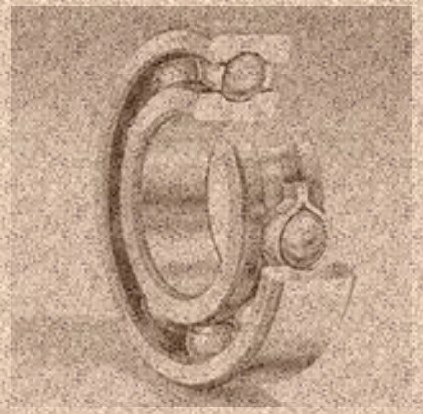
Crossed belt

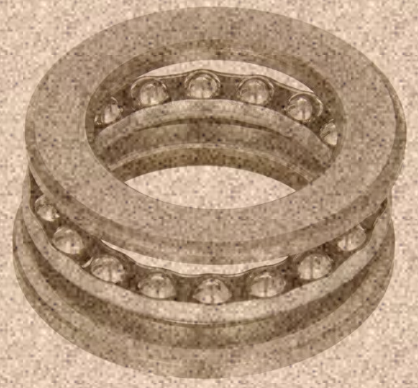
- Types of Belts:- Flat, Round, V Belt and Timing.

- Flat: The belt has a rectangular cross-section. Crowned pulleys are used to keep the belts from running off the pulleys.
- Round: The belt has a circular cross-section and is used with grooved pulleys
- V belt: V-belts are used with grooved pulleys. A number of them can be used on a single wheel and so give a multiple drive.
- Timing: Timing belts require toothed wheels, having teeth which fit into the grooves on the wheels. They transmits power at a constant angular velocity ratio.

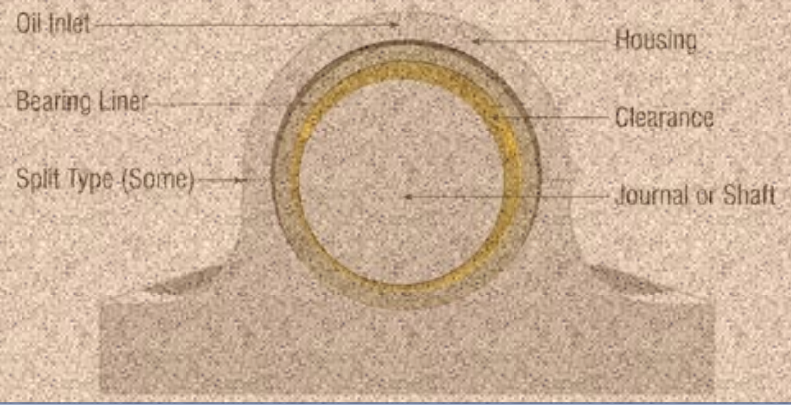
Bearings

- Function of bearing is to guide with minimum friction.
  - To support rotating shaft – Radial bearing.
  - To withstand axial forces – Thrust bearing.

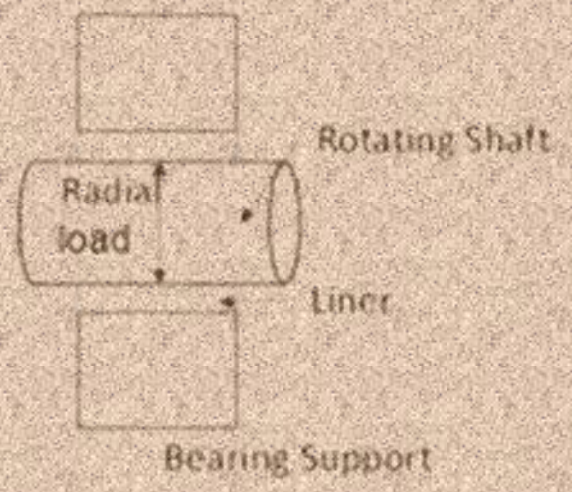




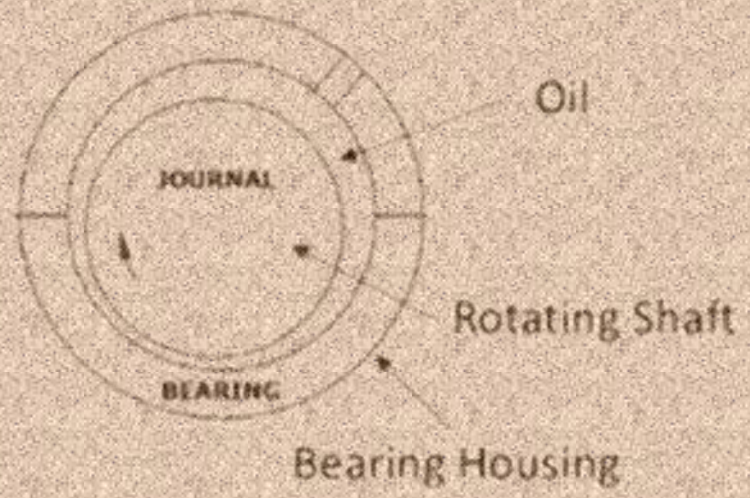
- Plain Journal Bearing:- Journal-shaft
  - Shaft is loaded in radial direction.
  - Bearing consists of some suitable fitted between shaft and support. (called inserts)
  - Inserts may be consists metal, Al alloys, Cu alloys, Bronze or a polymer as nylon.
  - Insert provide lower coefficient of friction.



- The lubricant may be.
  1. Hydrodynamic – shaft rotates in oil.
  2. Hydrostatic – lubricant provided under pressure.
  3. Solid film – graphite or molybdenum disulphide.
  4. Boundary layer – thin layer of lubricant.



Plain Journal Bearing



Hydrodynamic Journal Bearing

- Selection of Bearings
  - Dry sliding Bearings – Small diameter shafts, low load, low speed.
  - Ball and Roller Bearings – Much wider range of diameter, load and speed.
  - Hydrodynamic Bearings – Large diameter and high load.
- Failure of ball and roller bearings – occurs as a result of fatigue.
  - Life of bearing is defined as the number of millions of shafts revolutions that 90% of the bearings are expected to exceed before failing.
  - This life depends upon load applied.

Pneumatic & Hydraulic Signals

- Pneumatic signals:-
  - They are used to control final control elements, even when the control signal is electrical.
  - Such signals can be used to actuate large valves & other high power control devices.
  - Drawback: compressibility of air.
- Hydraulic signals:-
  - High power control devices.
  - More expensive.
  - Hazard associated with oil leak.

Fluid Power: Pneumatics vs. Hydraulics

- Fluid power denotes the use of a pressurized fluid to drive linear or rotary actuators.
- The subject can be broadly divided into two fields: pneumatics and hydraulics.
- In the first, the working fluid is compressed air, and in the second, it usually is oil (sometimes water-oil emulsions).
- The two fields have a great deal in common, but there are also some basic differences:

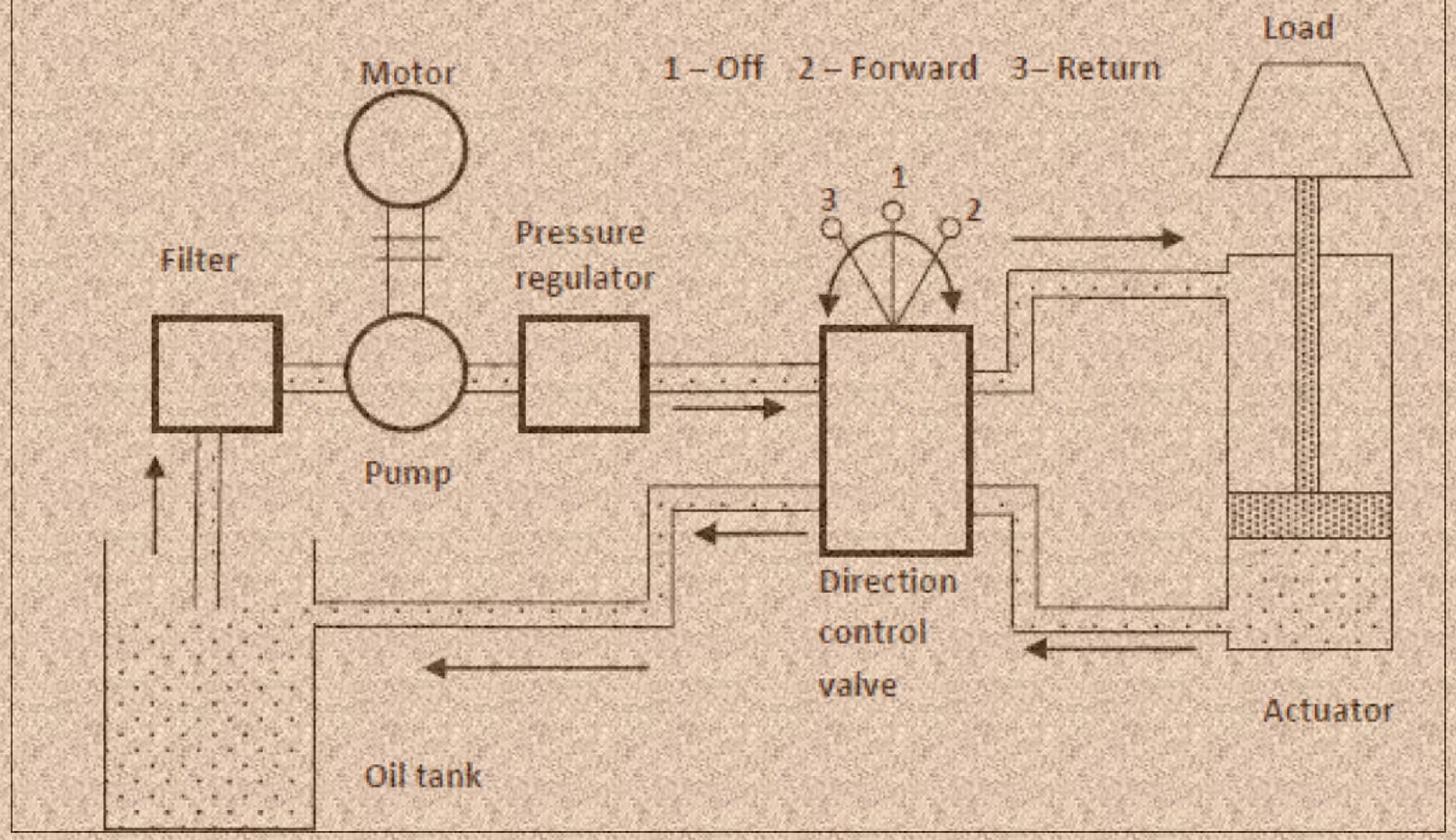
- Pressure Levels:
  - In industrial pneumatic circuits range from 5 to 10 bar,
  - whereas hydraulic circuits commonly operate at pressures up to 200 bar, or even much higher.
- Actuating Forces:
  - Because of the relatively low air pressures used, pneumatic actuators can produce only low or medium size forces,
  - whereas hydraulic actuators are suitable for very high loads.
- Element Cost: Hydraulic cylinders and valves can cost from 5 to 10 times more than similar-size pneumatic elements.

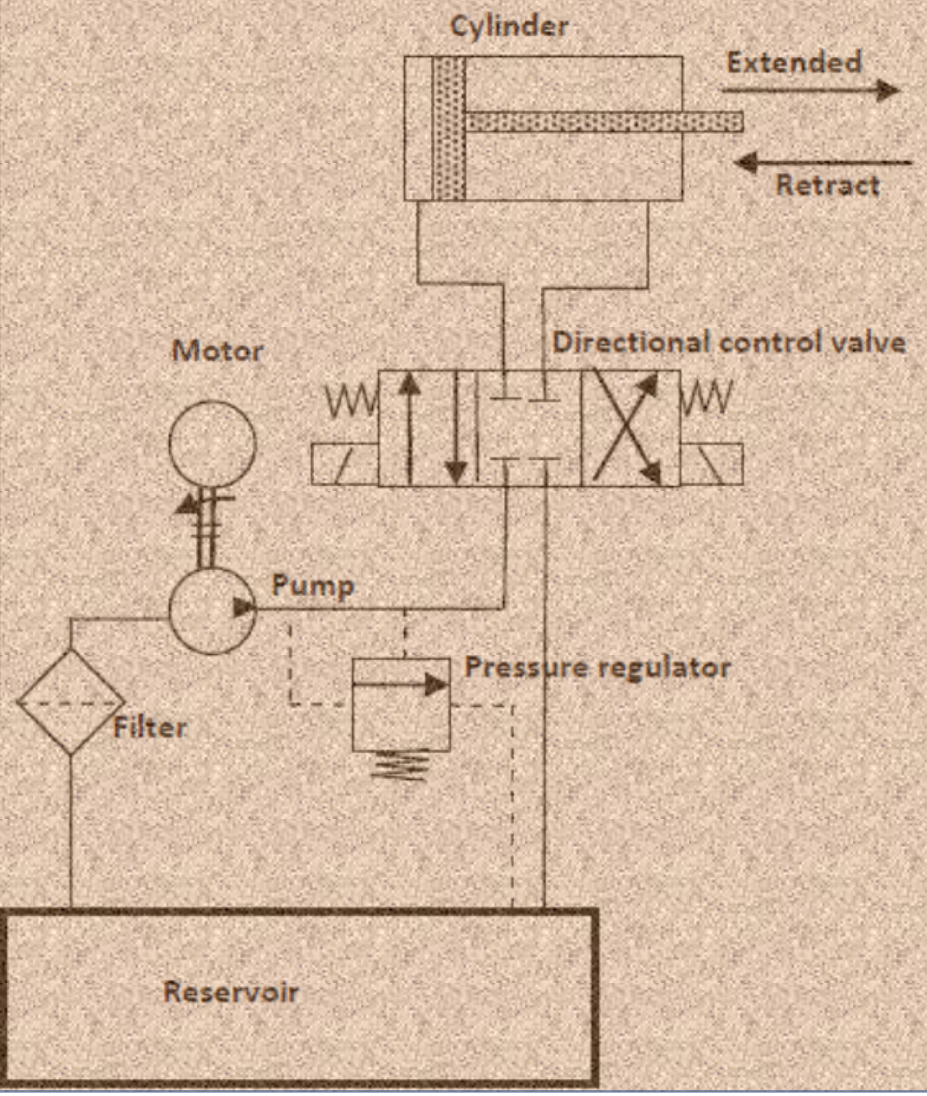
atm	ata (kg/cm^2)	Torr (mm Hg)	in Hg (32°F)	mm water (4°C)	in water (60°F)	bar	Mpa	Kpa	PSI (lb/in)
1	1.033	760	29.92	10332.56	406.79	1.013	0.1013	101.32	14.69

- Transmission Lines:
  - Hydraulic transmission lines are usually made of metal tubing needed to withstand the high working pressures and to avoid leaks. Strong
  - In pneumatics, flexible plastic tubing is used, and the fittings can usually be connected by hands.
  - Also, in hydraulic systems, return lines are needed to return the oil from each cylinder back to the reservoir.
  - In pneumatic systems, only a single line is needed, since the air is simply exhausted back to the atmosphere after it has done its job.

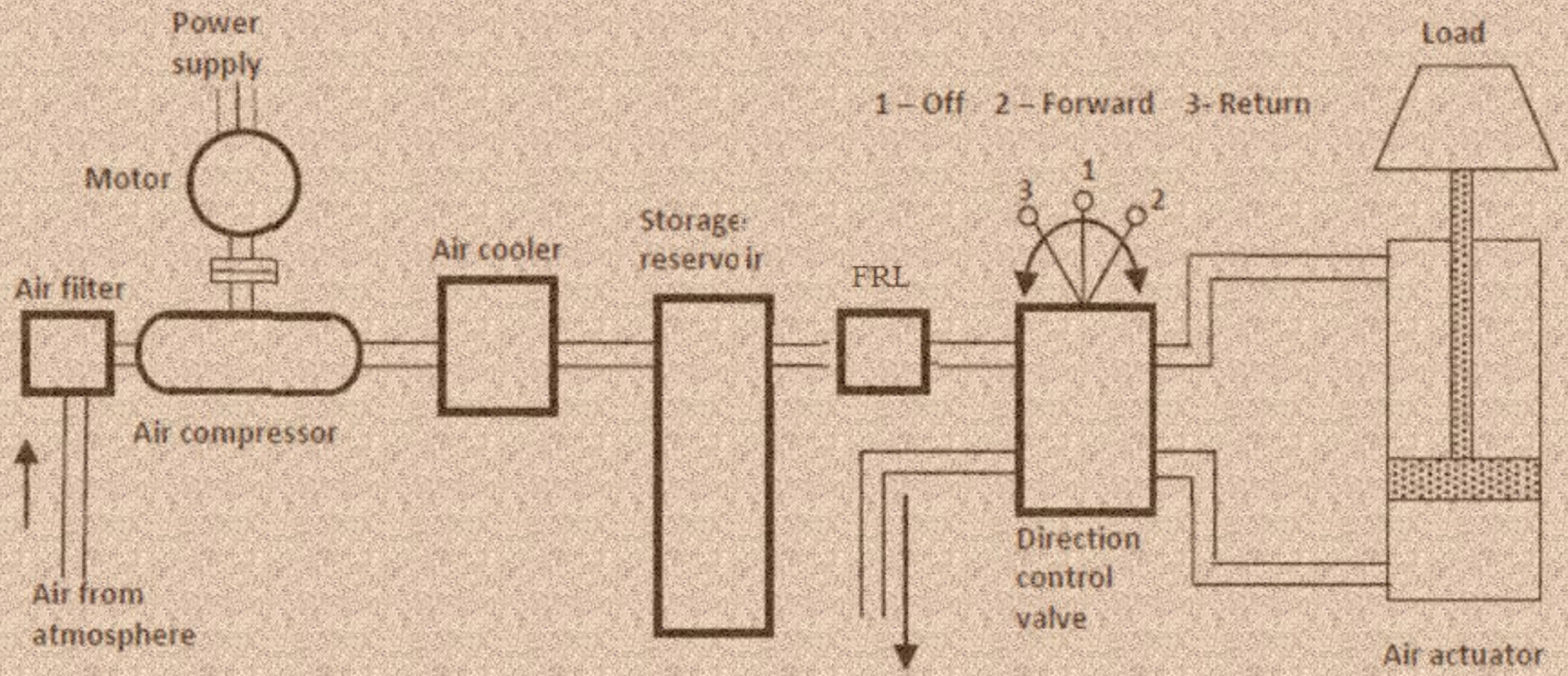
- Speed Control:
  - Because of the compressibility of air, it is difficult to control the speed of pneumatic cylinders or motors accurately.
  - Therefore, whenever constant actuator speeds are required–despite sudden load changes–a hydraulic system should be used.
- Actuation Speeds:
  - Since compressed air expands very quickly, the piston velocities in pneumatic cylinders are usually very high, provided the actuating valves and air supply tubing are properly sized.
  - In hydraulic cylinders, piston velocity is usually low, being determined by the flow rate of the pump.

BASIC COMPONENTS OF HYDRAULIC SYSTEM



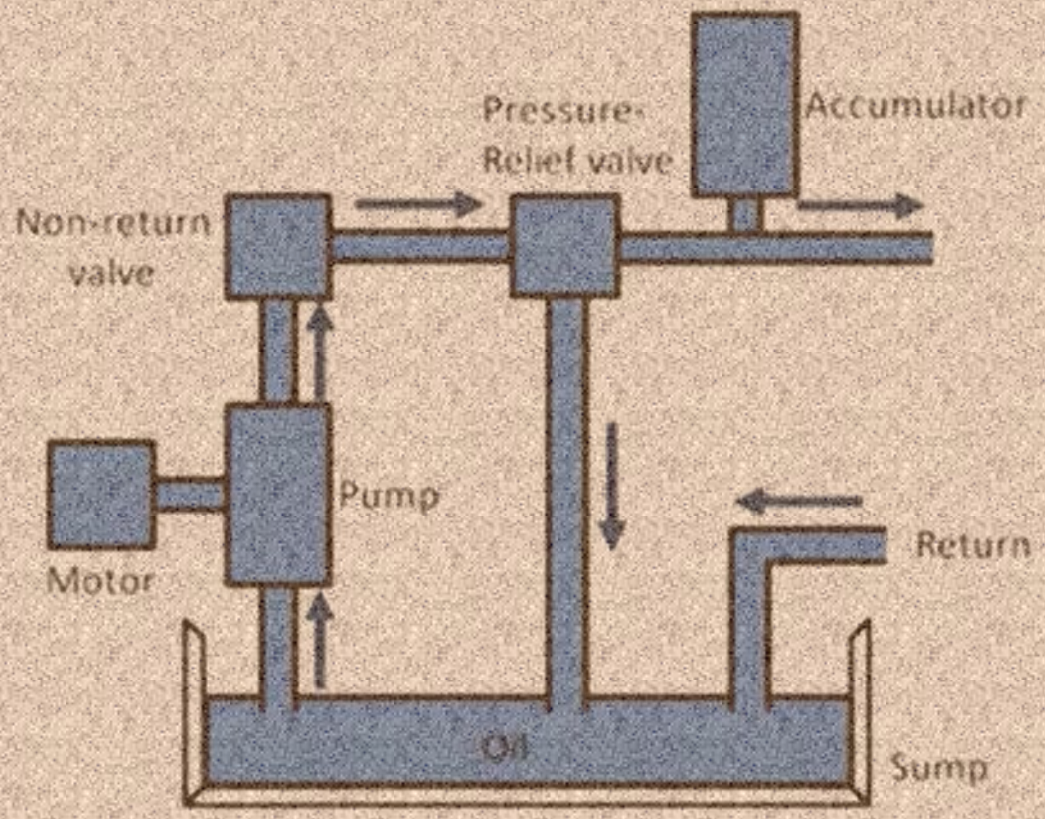


Basic Components of Pneumatic System

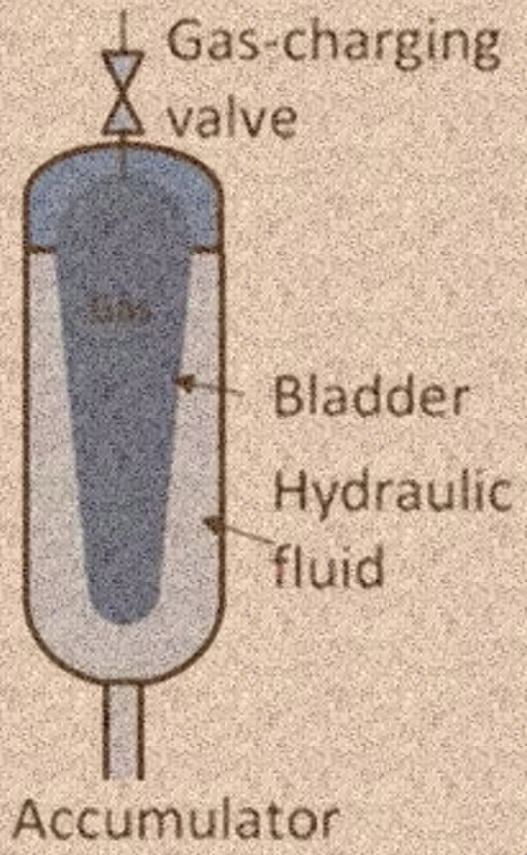


Power Supplies

- Hydraulic power supply
- With hydraulic system, pressurized oil is provided by a pump driven by an electric motor.
- The pump pumps oil from a sump through a non-return valve and an accumulator to the system, from which it returns to the sump.



- Accumulator: Smooth out any short term fluctuation in the output oil pressure.
  - If pressure ↑, bladder vol.↓, liquid vol. ↑, pressure ↓.
  - If pressure ↓, gas vol. ↑, liquid vol. ↓, pressure ↑.



Introduction

- Switching devices (control signal switches on or off to some electrical device)
  - Mechanical - relays
  - Solid state devices - diodes, transistors
- Solenoid type devices - used in hydraulic/pneumatic systems- current through a solenoid is used to actuate a soft iron core
- Drive systems – dc and ac motors
- Aim is to select a motor for a mechatronic application

Electromagnetic Principles

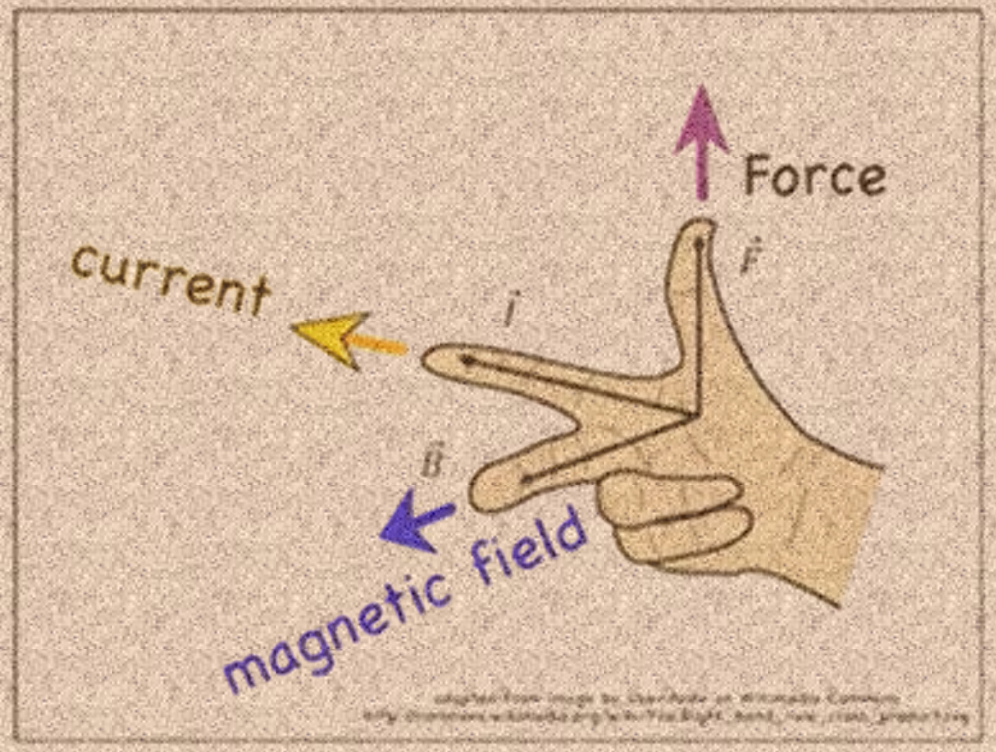
- When a current carrying conductor is moved in a magnetic field, a force is produced in a direction $\perp^r$ to the current and magnetic field direction.
- Lorentz's law in vector form is:

$$\vec{F} = \vec{I} \times \vec{B}$$

Where: $\vec{F}$ = Force vector (per unit length of conductor).

$\vec{I}$ = Current vector.

$\vec{B}$ = Magnetic field vector.



Relationship is given by right hand analogy

Field Intensification within a Coil

- Magnetic flux through a coil

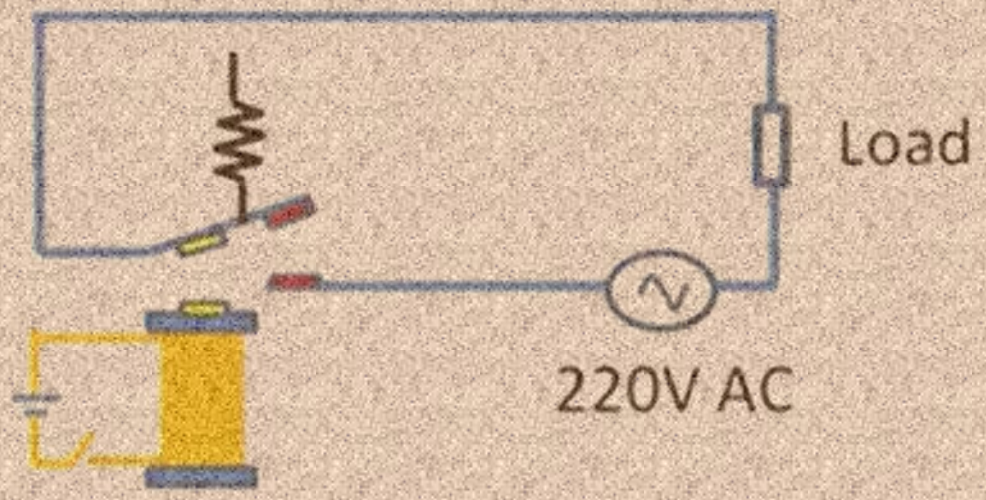
$$\phi \propto I.n$$
$$= K.I.n$$

Where: K = Constant (function of permeability of material within the coil)

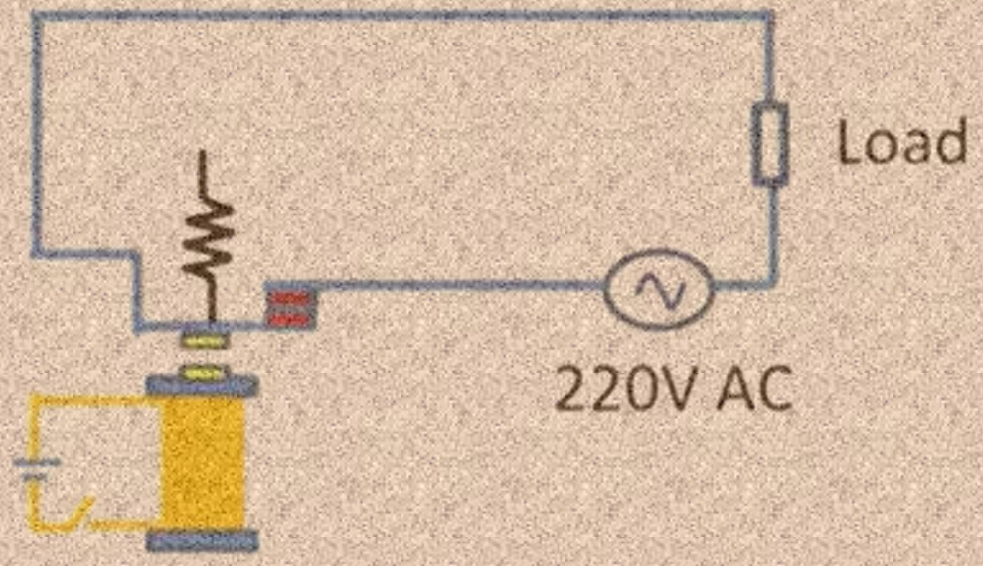
- Permeability – Characteristic how easily magnetic flux penetrates the material.
- Iron permeability = 100×Air.
- Cores laminated to reduce eddy current losses.

Relays

- An example of a electromagnetic switch.
- Used in applications to turn on or off a circuit by a low power signal.
- When there is a current through the solenoid of the relay, a magnetic field is produced which attracts the iron armature, moves the lever, and so
  - closes the normally open (NO) switch contacts
  - opens the normally closed (NC) switch contacts.



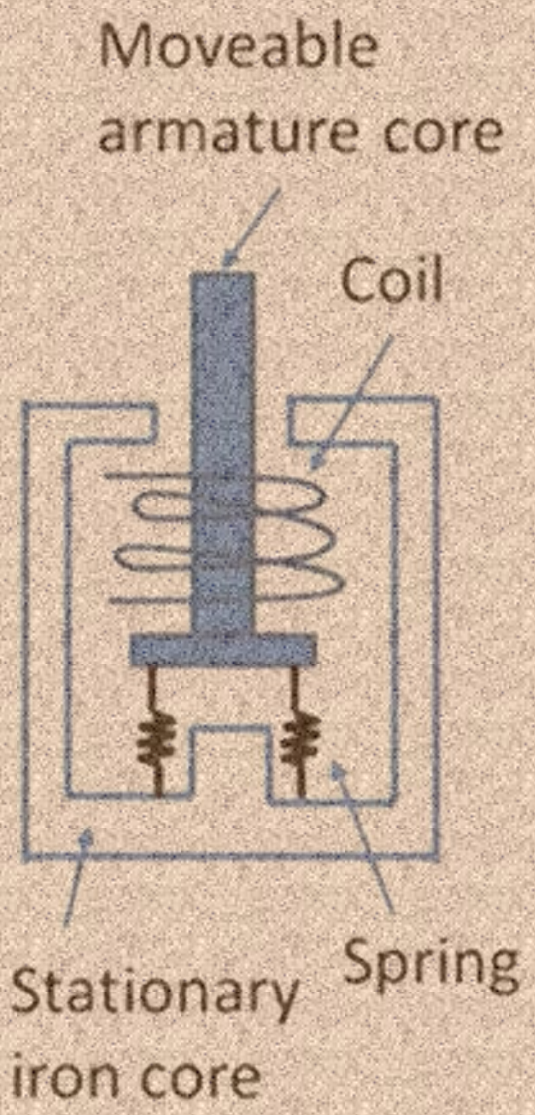
Normally open (NO)

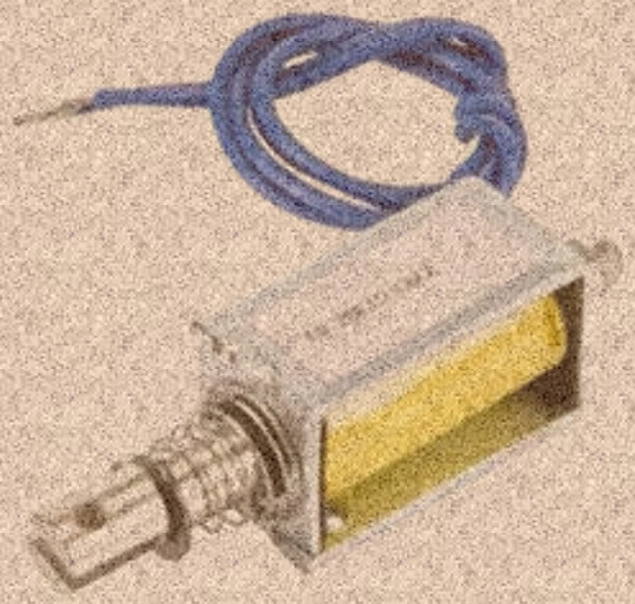


Normally closed (NC)

Solenoids

- It consists of a coil of electrical wire with an armature which is attracted to the coil when a current passes through it and produces a magnetic field.
- The movement of the armature contracts a return spring which then allows the armature to return to its original position when the current ceases.

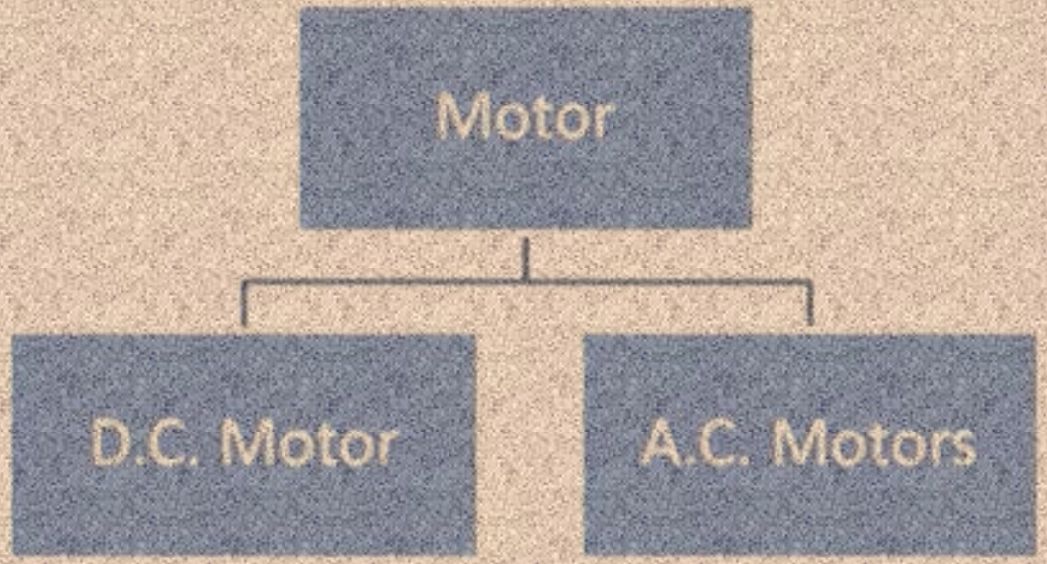




Push pull type solenoid

Electric Motors

- Electric motors used in position control systems or speed control systems.



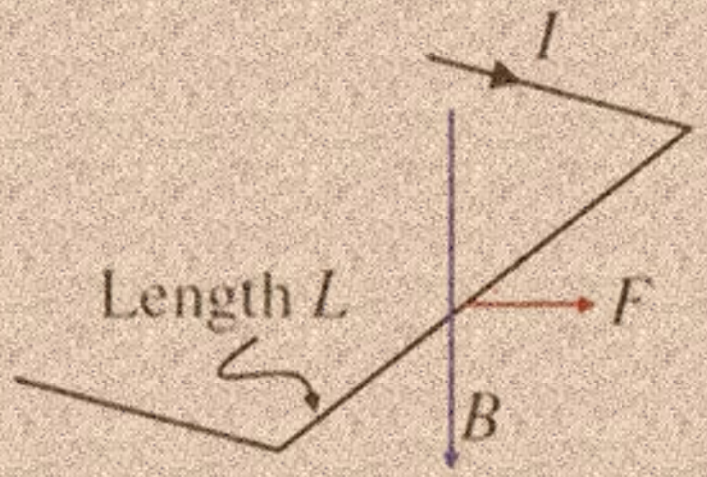
- D.C. Motors: Mostly used in modern control systems

Basic Principles

1. A force in exerted on a conductor in a magnetic field when a current passes through it.

   Force $F = BIL$ (Lorentz's law)

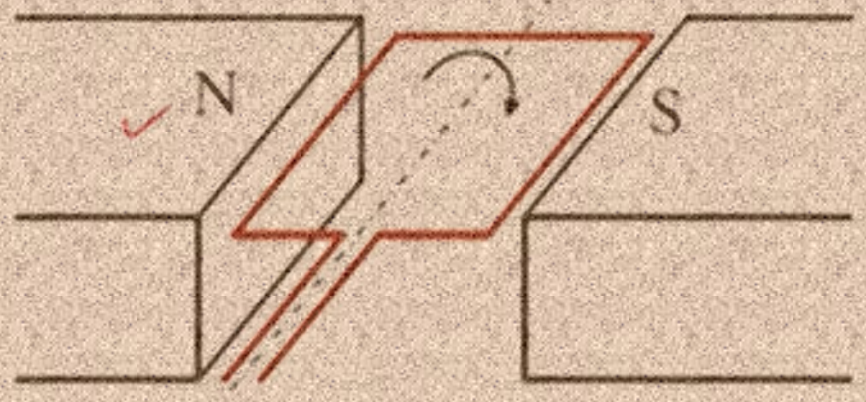
2. When a conductor moves in a magnetic field, then an e.m.f. is induced across it.

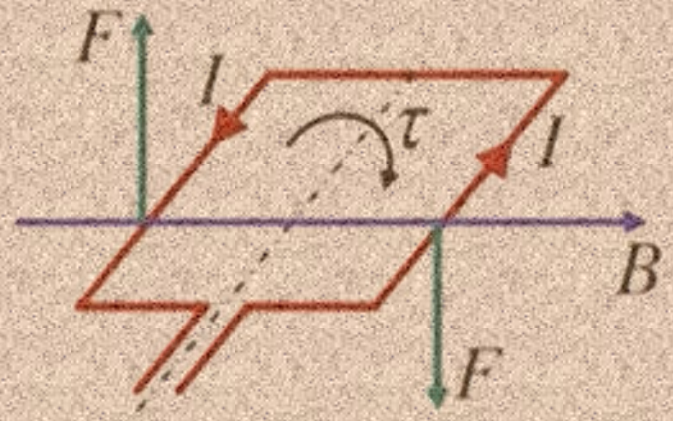


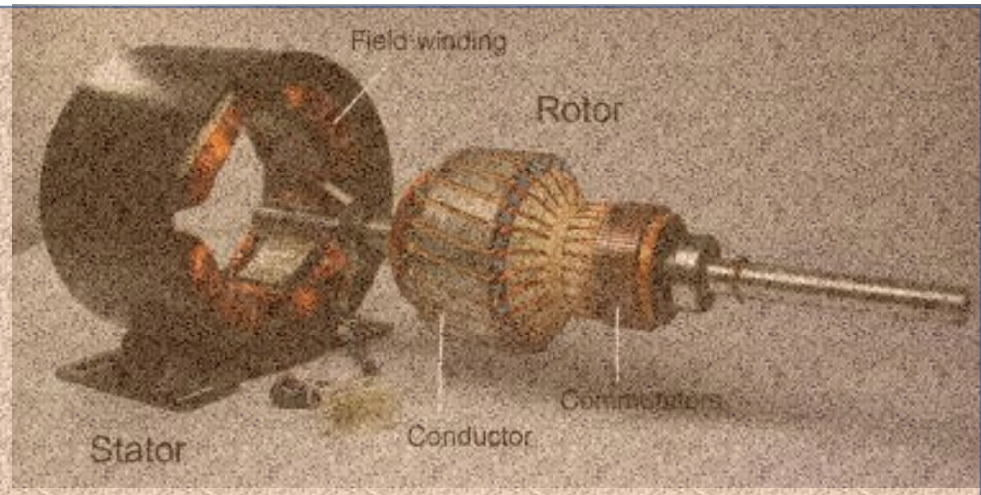
- The induced e.m.f. (e) is equal to the rate at which the magnetic flux ϕ swept through by the conductor changes. (Faraday's law) i.e. $e = -\frac{d\phi}{dt}$.
- The –ve sign is because the e.m.f. is in such a direction as to oppose the charge producing it (Lenz's Law).
- i.e., direction of induced e.m.f. is such that it produces the current which sets up magnetic fields which tend to neutralize the change in magnetic flux linked by the coil and which was responsible for the e.m.f.
- That is why, it is also called as back e.m.f.

D. C. Motors

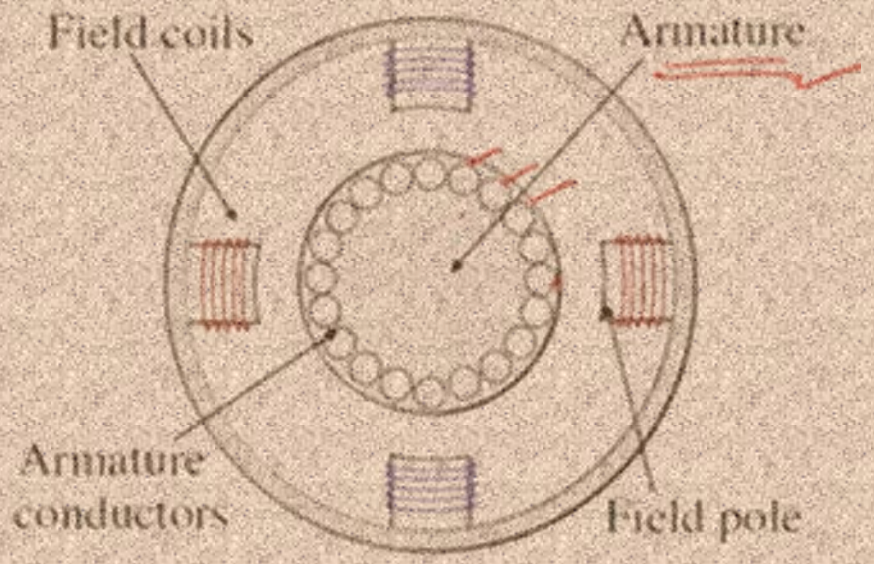
- A loop of wire which is free to rotate in the field of permanent magnet.
- When a current is passed through the coil, a force act on the side right angle to field.
- For rotation to continue, when the coil passes through the vertical position, the current direction through the coil has to be reversed.







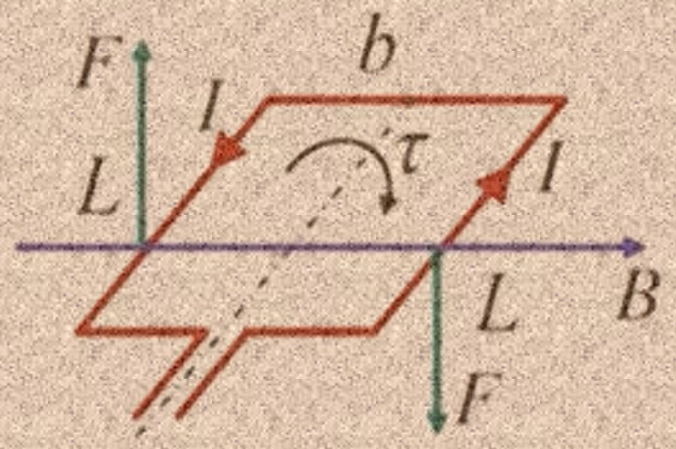
- In the conventional d.c. motor, coils of wire are mounted in slots on a cylinder of magnetic material called the armature.
- The armature is mounted in the magnetic field produced by field poles.
- The ends of each armature coil are connected to adjacent segments of a segmented ring called the commutator with electrical contacts made to the segments through carbon contacts called brushes.



A four-pole d.c. motor

Permanent Magnet D.C. Motor

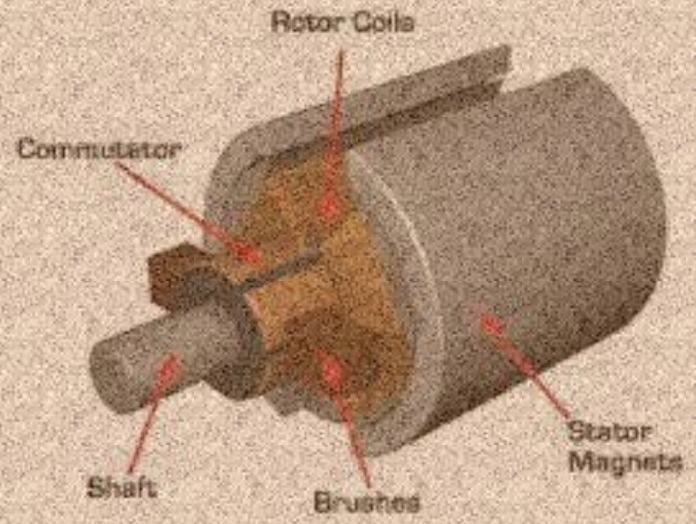
- Let a permanent magnet d.c. motor, the permanent magnet giving a constant value of flux density.
- Force at right angle to conductor = BIL
- Force with N such conductors = $NBIL$
- Forces result in a torque T about the coil axis = Fb {b = width of coil}
- Torque $T = Fb = NBILb = (NBLb)I = K_t I$
  {Here K_t = torque constant}



Armature

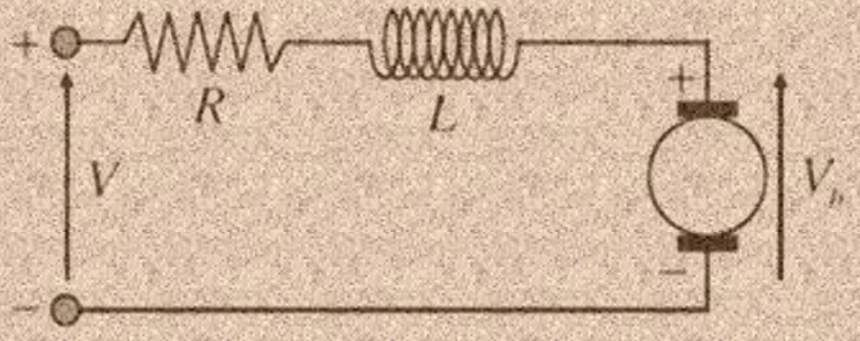
- Since armature is rotating in a magnetic field, electromagnetic induction will occurs and back e.m.f. will be induced.
- The back e.m.f. V_b is $\propto$ rate in which flux linked by the coil changes.
- For a constant magnetic field the back e.m.f. $\propto$ angular velocity (ω) of rotation.
- Thus back e.m.f. = $V_b = K_v\omega$.
  {Here K_v = back e.m.f. constant}

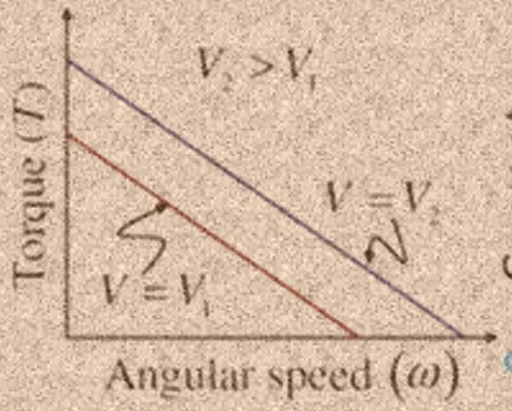
Permanent magnet DC motor
SEWOO Industrial Systems Co.,Ltd

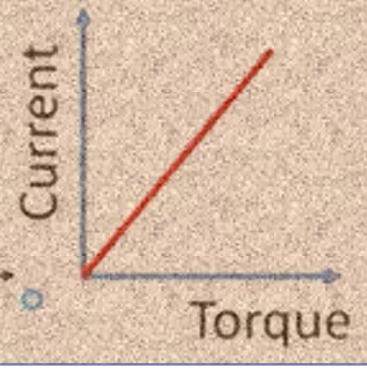


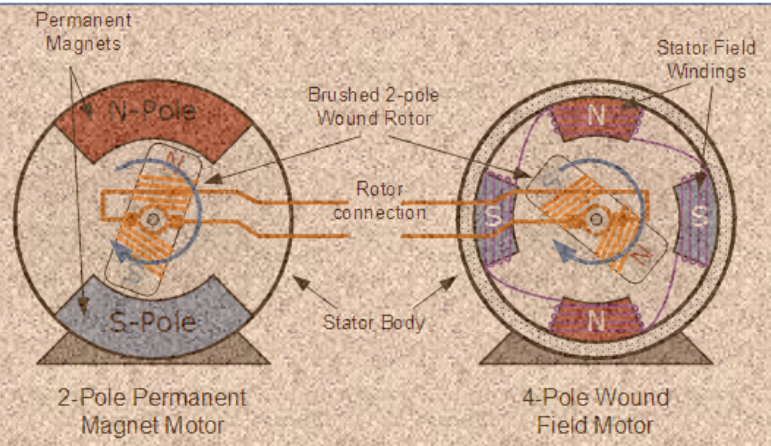
Equivalent Circuit of DC Motor

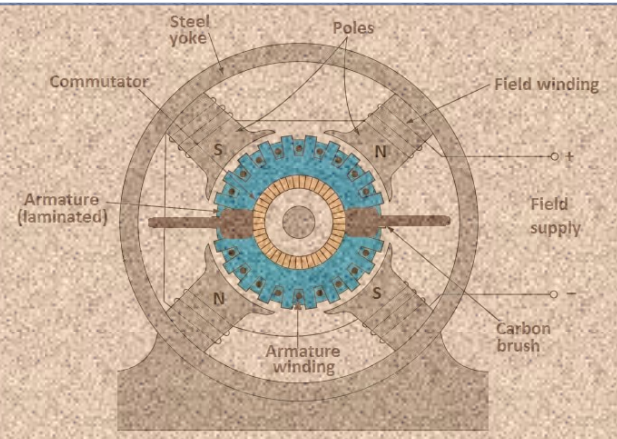
- Armature coil being represented by resistor R and inductor L in series.
- If inductance is neglected then:
  $I = \frac{(V - V_b)}{R} = \frac{(V - K_v\,\omega)}{R}$.
- Torque $T = K_t I = \frac{K_t}{R}(V - K_v\omega)$.
- During starting, $\omega = 0$, thus $T \propto V$.
- When no Load, $T = 0$, $\omega \propto V$.

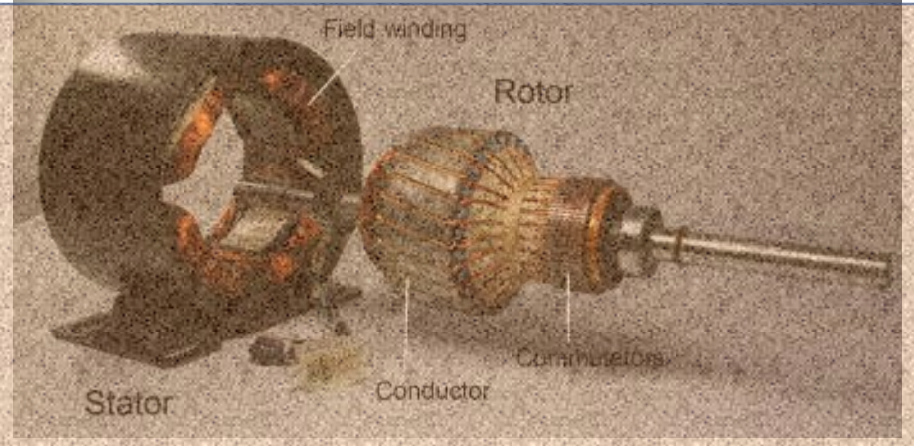




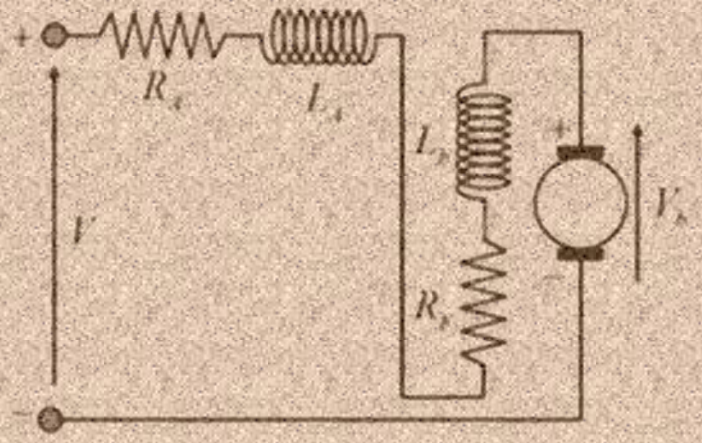






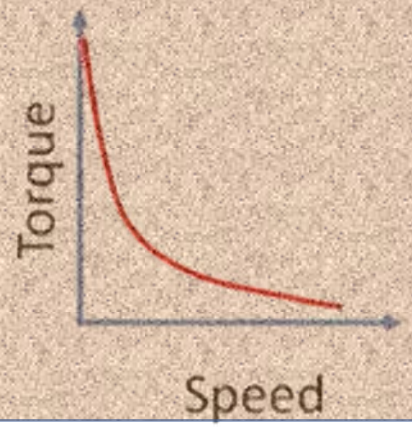


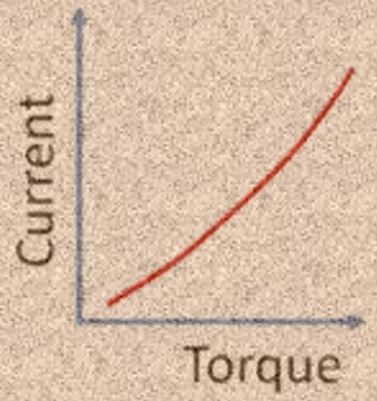
DC Motor with Field Coils



Series wound

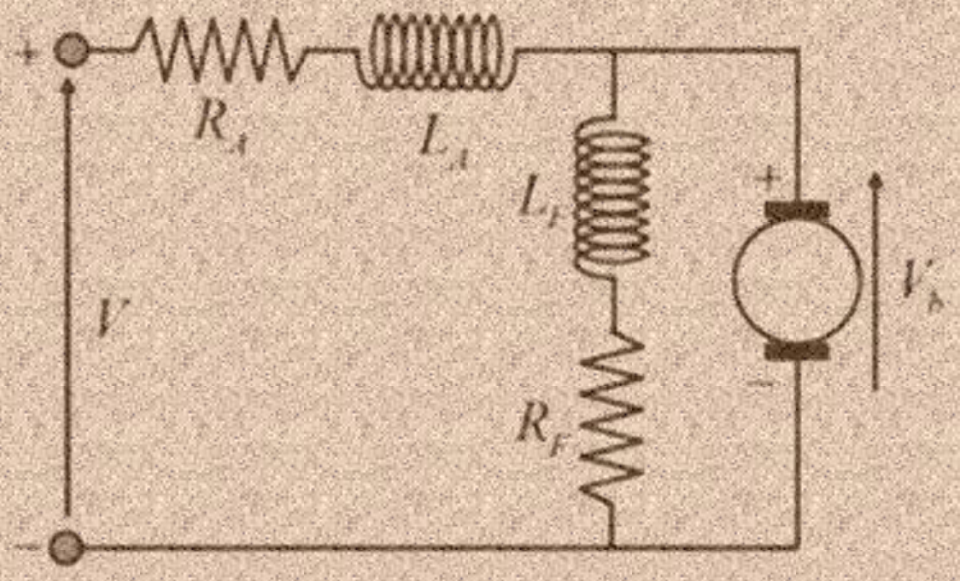
- Armature and Field coils are in series.
- Motor exerts higher starting torque and has greater no load speed.
- Reversing the polarity of supply has no effect on the direction of rotation of motor since both field and armature currents are reversed.

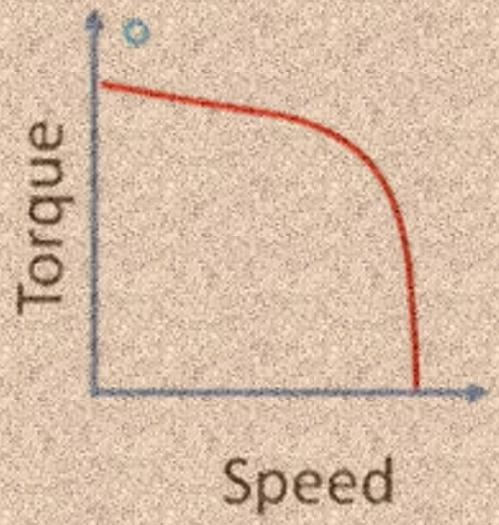


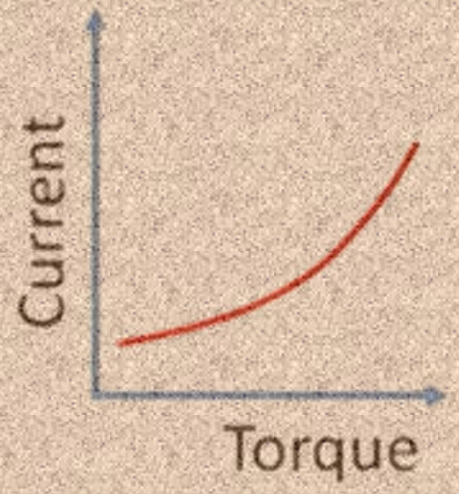


Shunt wound

- Armature and Field coils are in parallel.
- It provides lowest starting torque, lower no load speed, and good speed regulation.
- Constant speed regulation of load is possible.
- To reverse the direction of rotation either the armature or field supply is to be reversed.

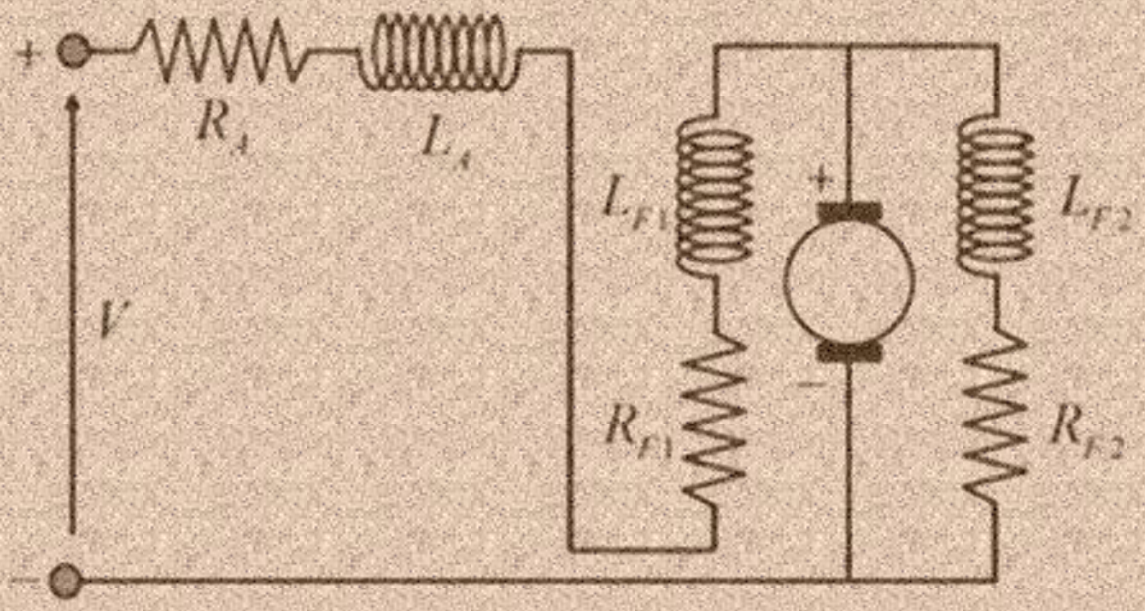


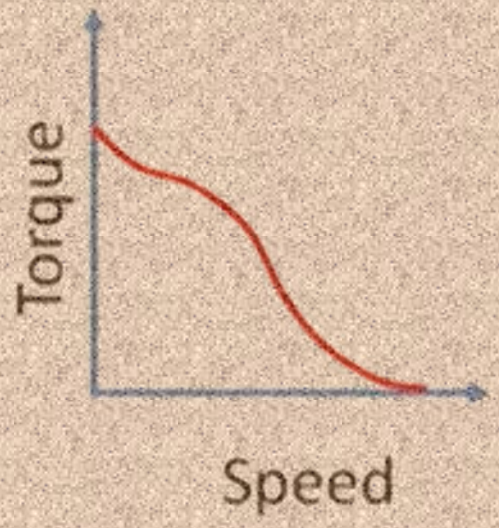


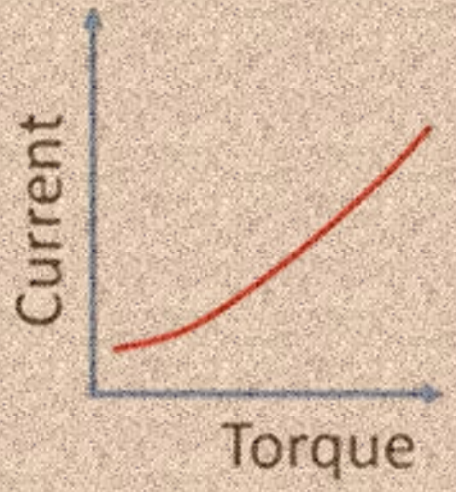


Compound Wound

- Gives combined features i.e. highest starting torque and better speed regulation.

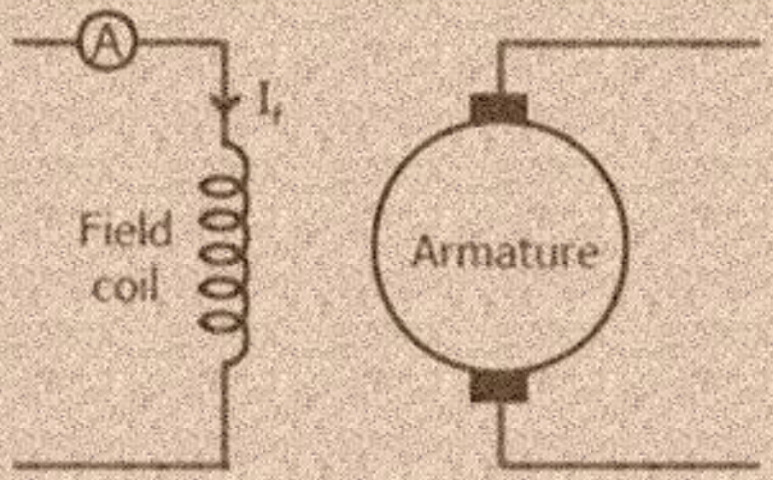




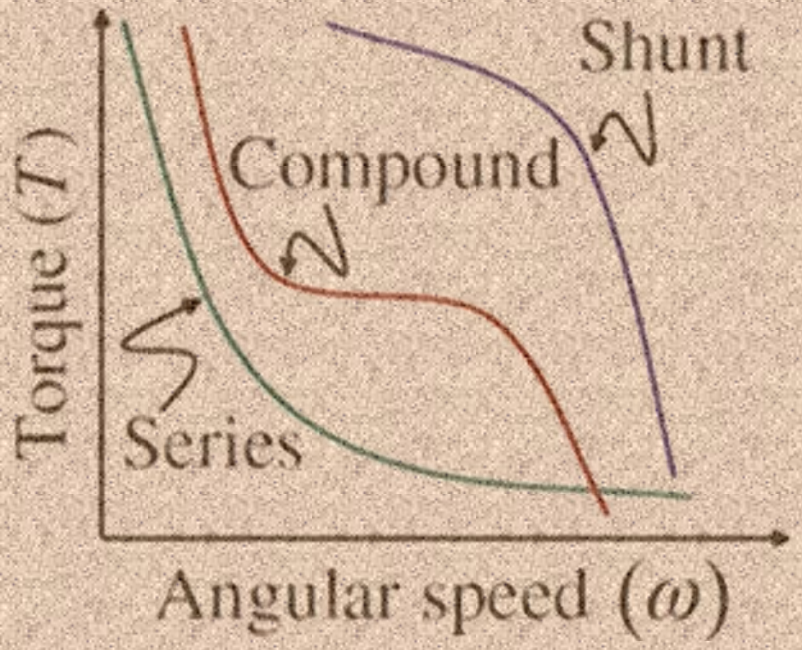


Separately Excited Motor

- Special case of shunt wound motor

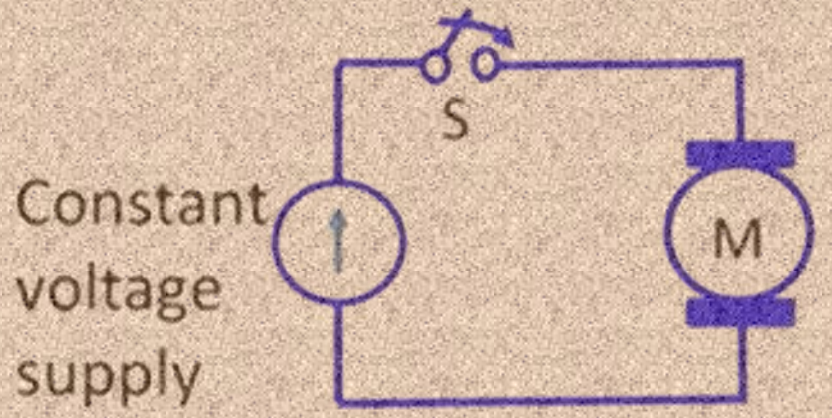


Comparison

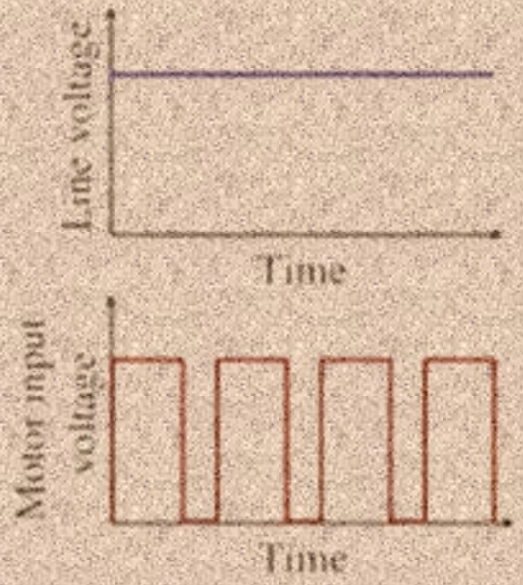


Control of DC Motors

- Speed of permanent magnet motor depends on the current through the armature coil.
- With a field coil motor the speed can be changed by either varying the armature current or the field current; generally with armature current.
- Thus speed control is possible by controlling the voltage applied to armature.
- Since fixed voltage supplies are often used, a variable voltage is obtained by an electronic application (switch).

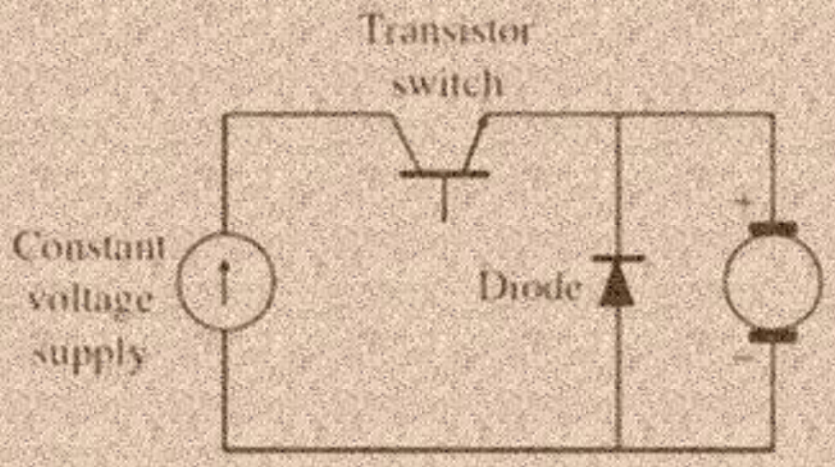


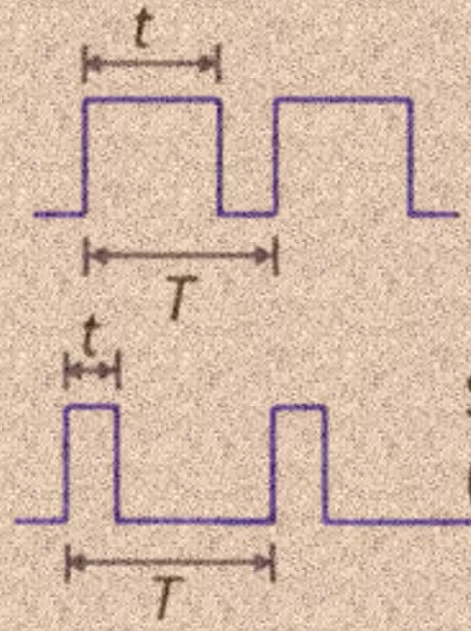
Principle of PWM



Varying the average armature voltage

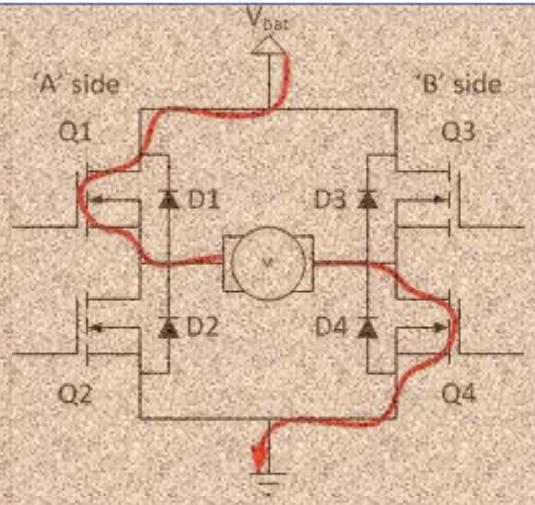
- Generally DC motors are controlled by control signals emerging from a microprocessor. In such cases, pulse width modulation (PWM) is used.
- The pulse width is modulated through a transistor which is switched on and off by means of signal applied to its base.
- The diode provides a path for current when the transistor is off and the motor is acting as a generator.
- This circuit can drive motor in one direction only.
- To drive it in both the direction H-bridge is used.

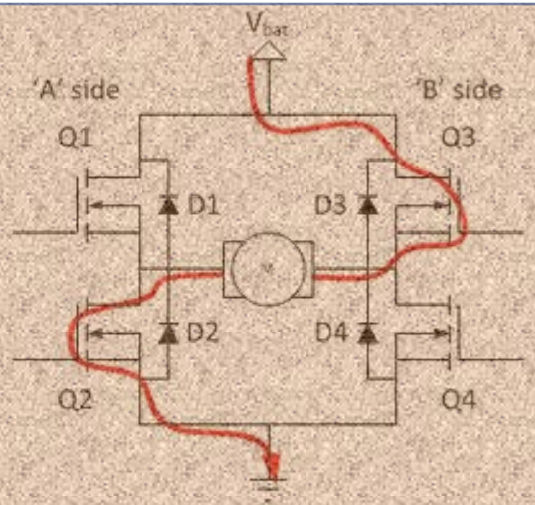




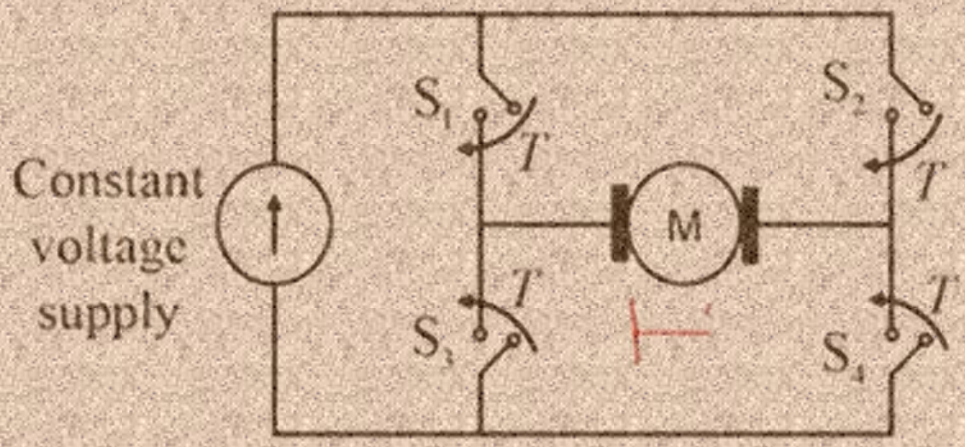
Faster (large t)

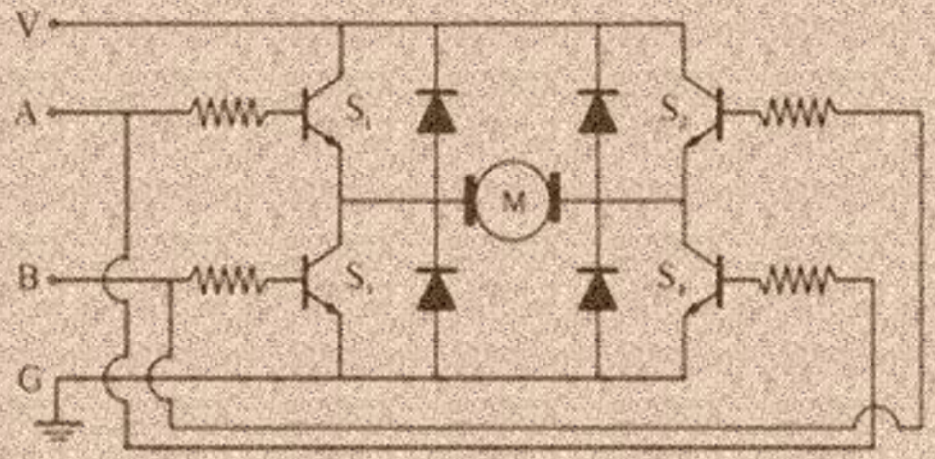
Slower (small t)





- The motor rotates in one direction when switches S_1 and S_4 are closed and rotates in opposite direction when switches S_2 and S_3 are closed.
- In practice, these switches are realized by transistors and diodes.
- For forward direction rotation, potential A will be high and potential B will be low, and for reverse direction rotation, potential A will be low and potential B will be high.

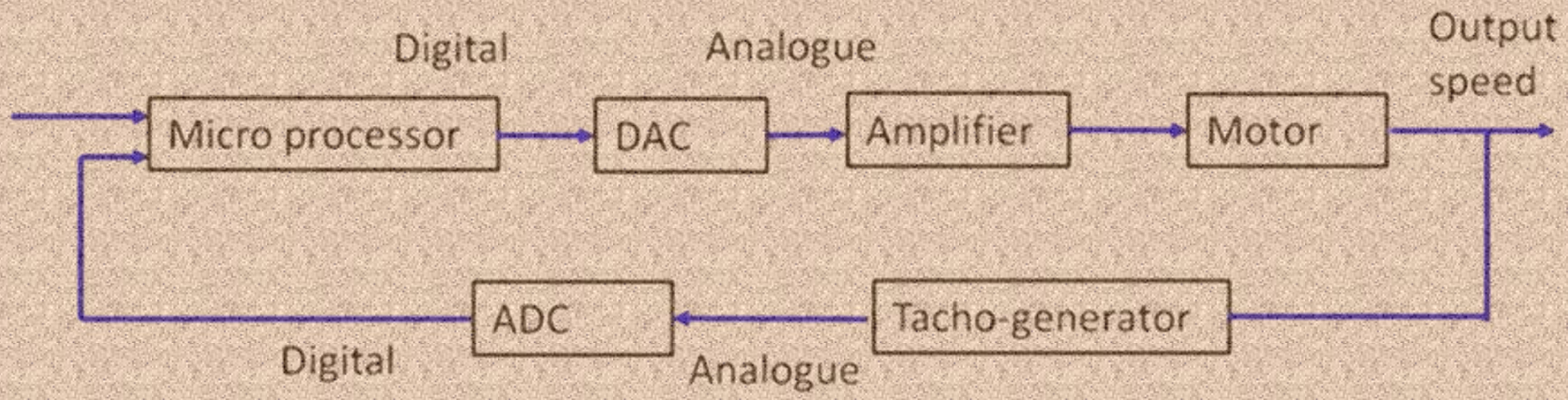




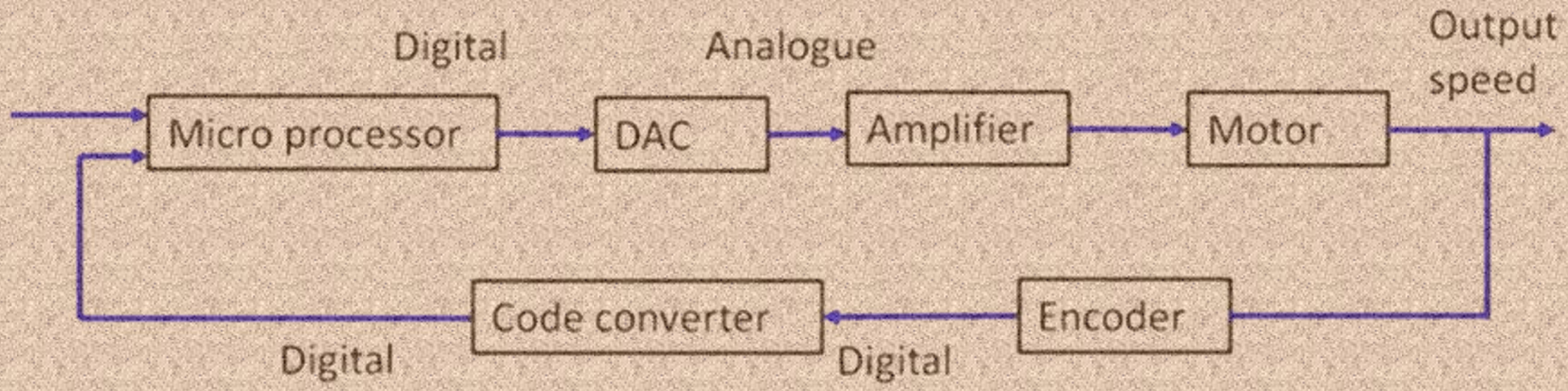
Here PWM signal applied to transistor base, controls the switching.

Speed Control with Feedback

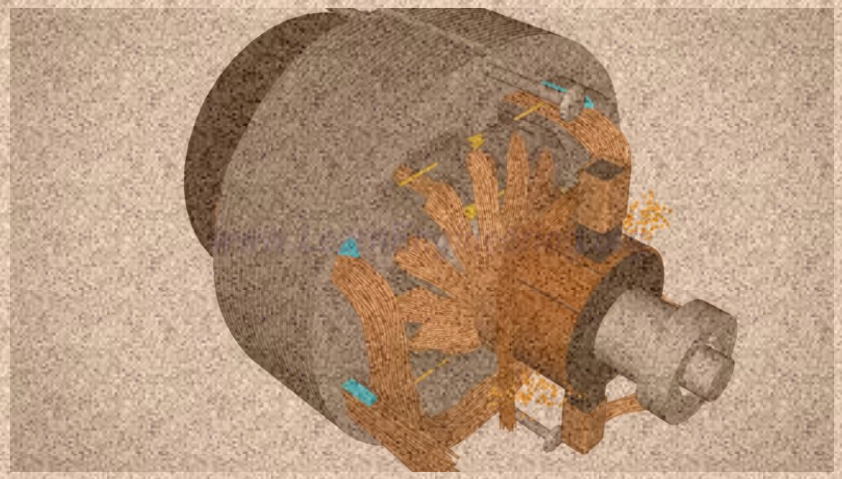
Feedback signal is provided by a tachogenerator



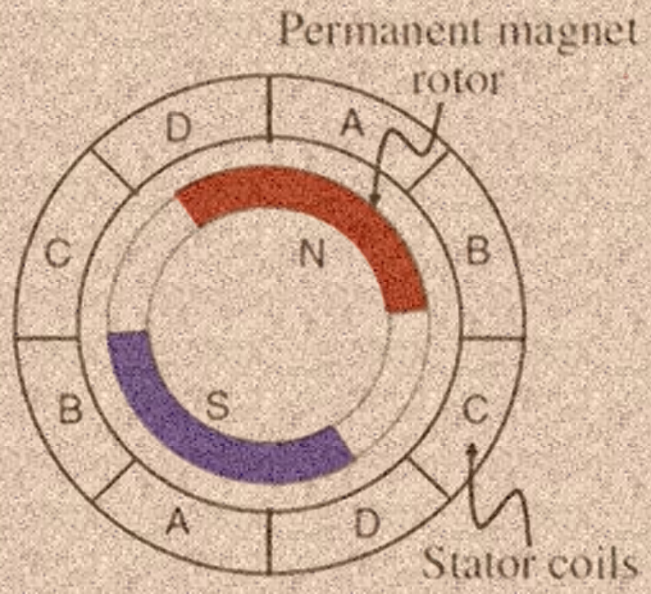
Feedback signal is provided by an encoder

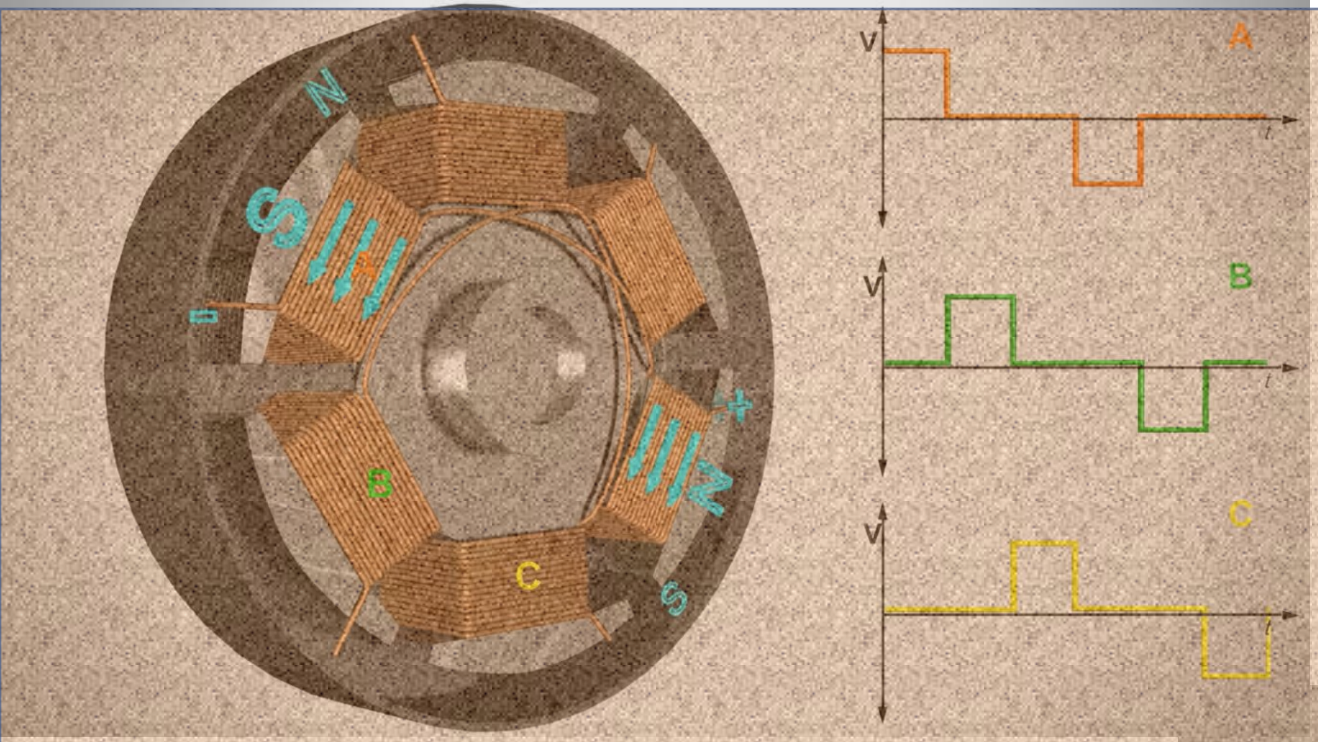


Brushless permanent magnet DC Motors



- <u>Simple DC Motor</u>
  - Commutator problem.
  - Spark/Wear.
  - Brush need to be periodically changed.
- <u>Brushless</u>
  - Sequence of stator coils.
  - Permanent magnet rotor.
  - Current carrying conductor in a magnetic field experience a force.
  - Newton's 3rd law, magnet will also experience an opposite and equal force.

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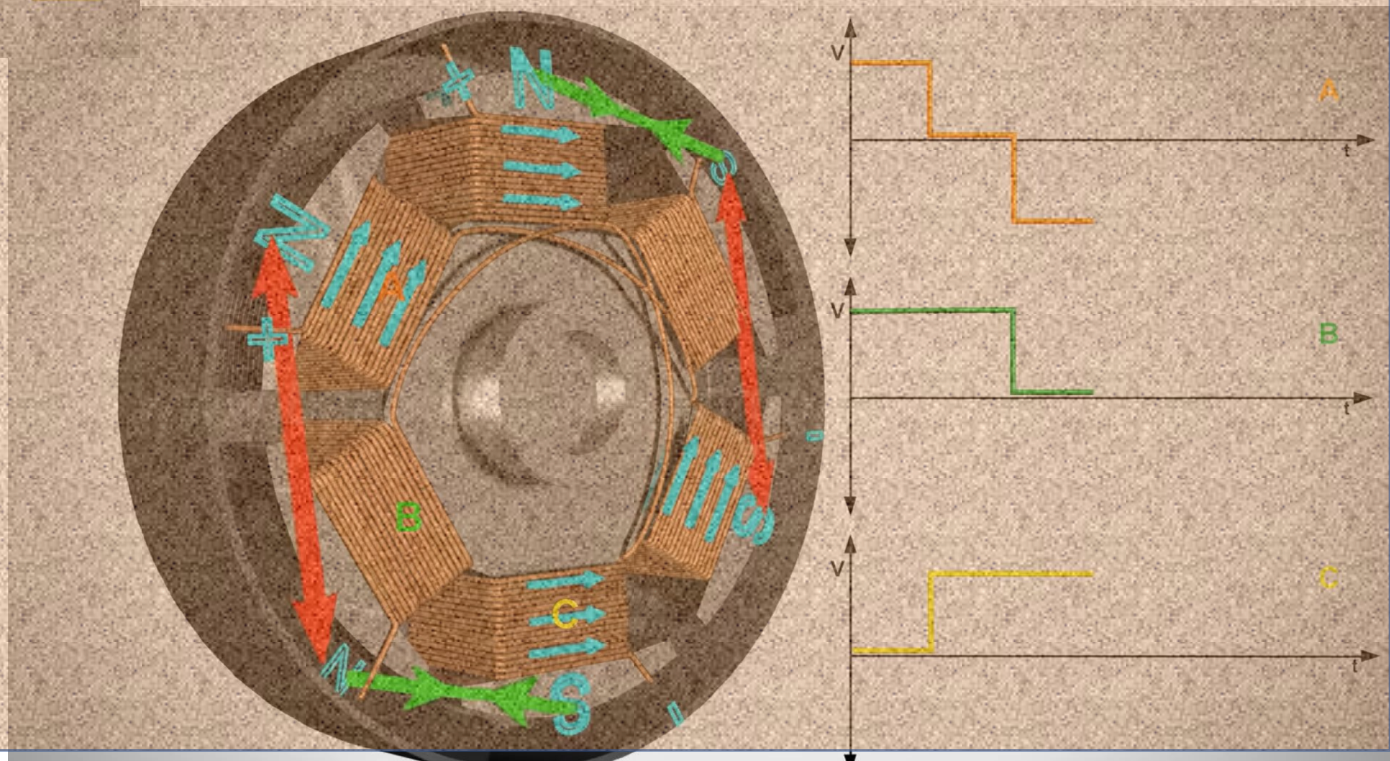
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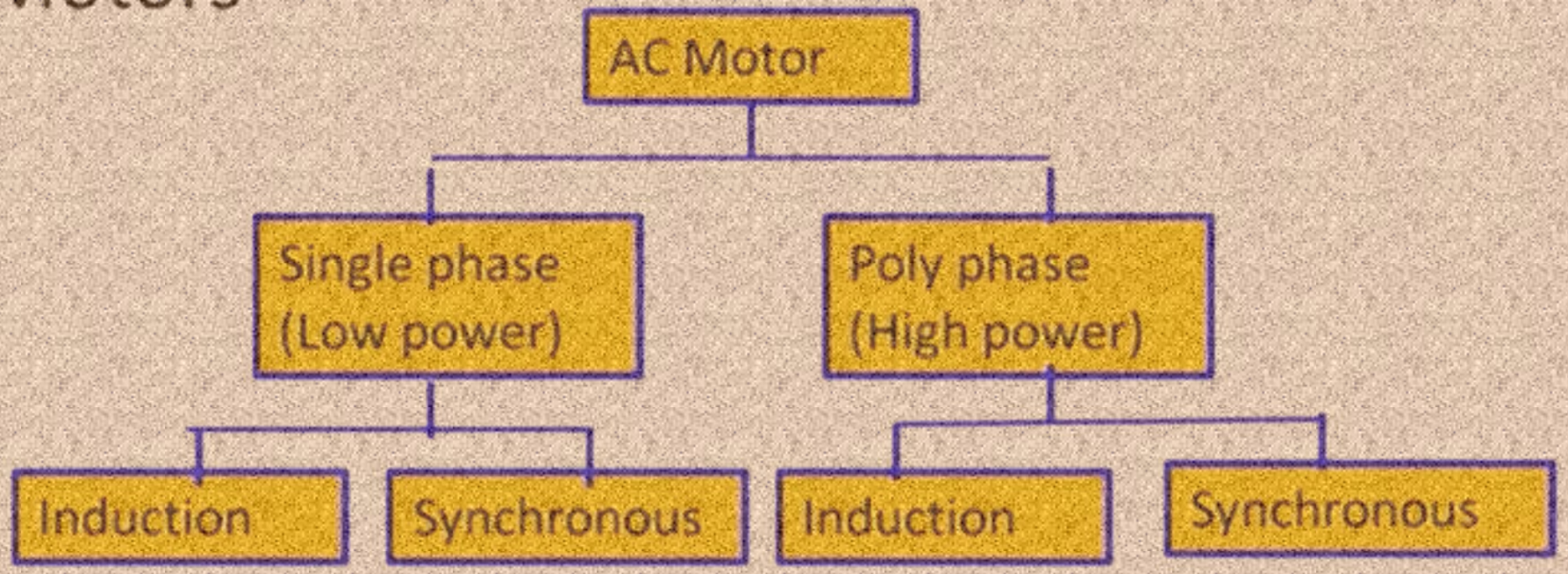
AC Motors

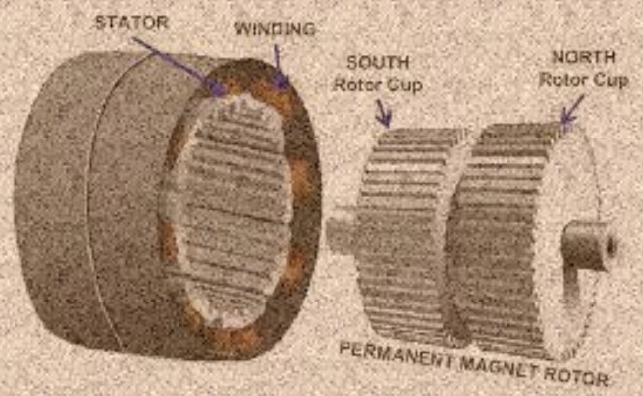


- AC Motors are cheaper compared to DC but their speed control is difficult.
- Speed control of AC motors is based on the provision of variable frequency supply, since the motor speed is determined by frequency of the supply.

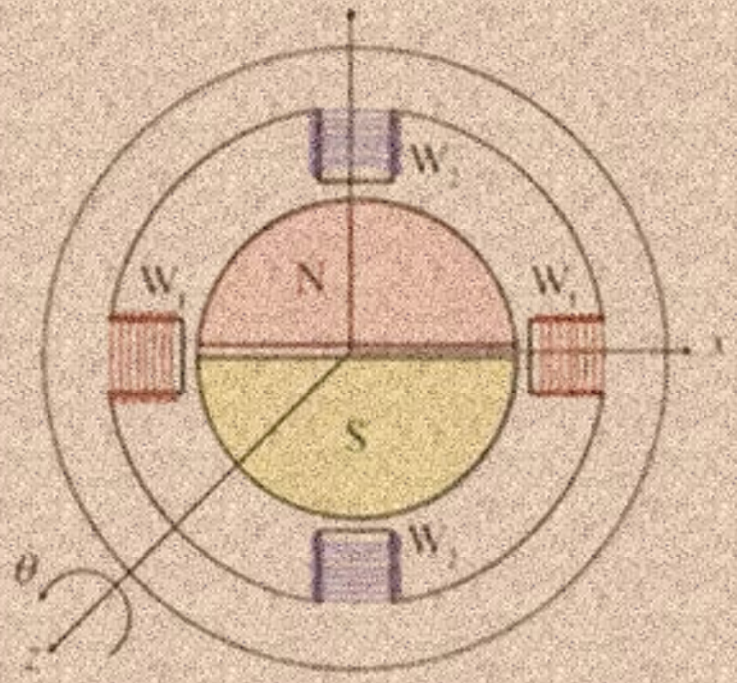
Stepper Motor

- Stepper motors are special type of D.C. motors.
- It can rotate in both directions, move in precise angular increments, sustain a holding torque at zero speed, and be controlled with digital circuits
- It moves in accurate angular increments, known as steps, in response to digital pulses sent to an electric drive circuit.
- The number and rate of the pulses control the position and speed of the motor shaft. Generally, stepper motors are manufactured with steps per revolution of 12, 24, 72, 144, 180, and 200, resulting in shaft increments of 30°, 15°, 5°, 2.5°, 2°, and 1.8° per step.

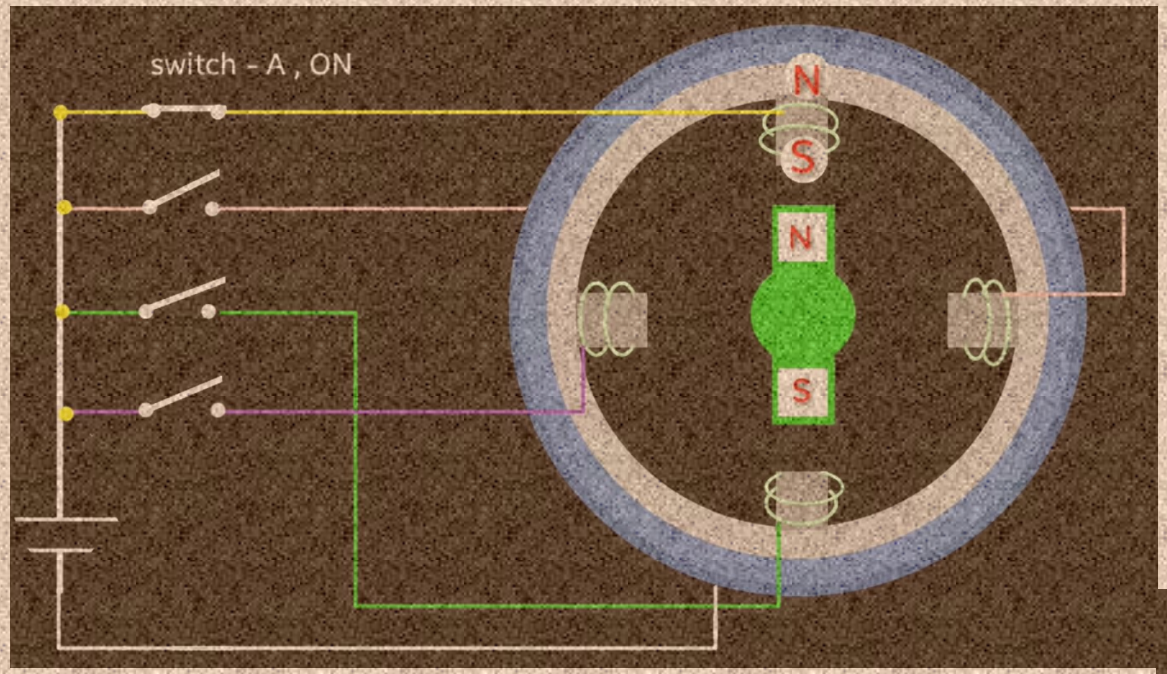
- Stepper motors are either bipolar (requiring two power sources or a switchable polarity power source), or unipolar (requiring only one power source).
- They are powered by DC sources and require digital circuitry to produce coil energizing sequences for motor rotation.
- Feedback is not always required for control, but the use of a position sensor can ensure accuracy.
- They are used in low-power position control applications i.e., less than 1 hp (746 W).



- They are classified as permanent magnet or variable reluctance stepper motors.
- In the case of a permanent magnet stepper motor, the stator consists of wound poles, and the rotor poles are permanent magnets.
- When we excite different stator winding combinations, the rotor moves and holds in different positions.



Permanent magnet stepper motor


switch - A , ON
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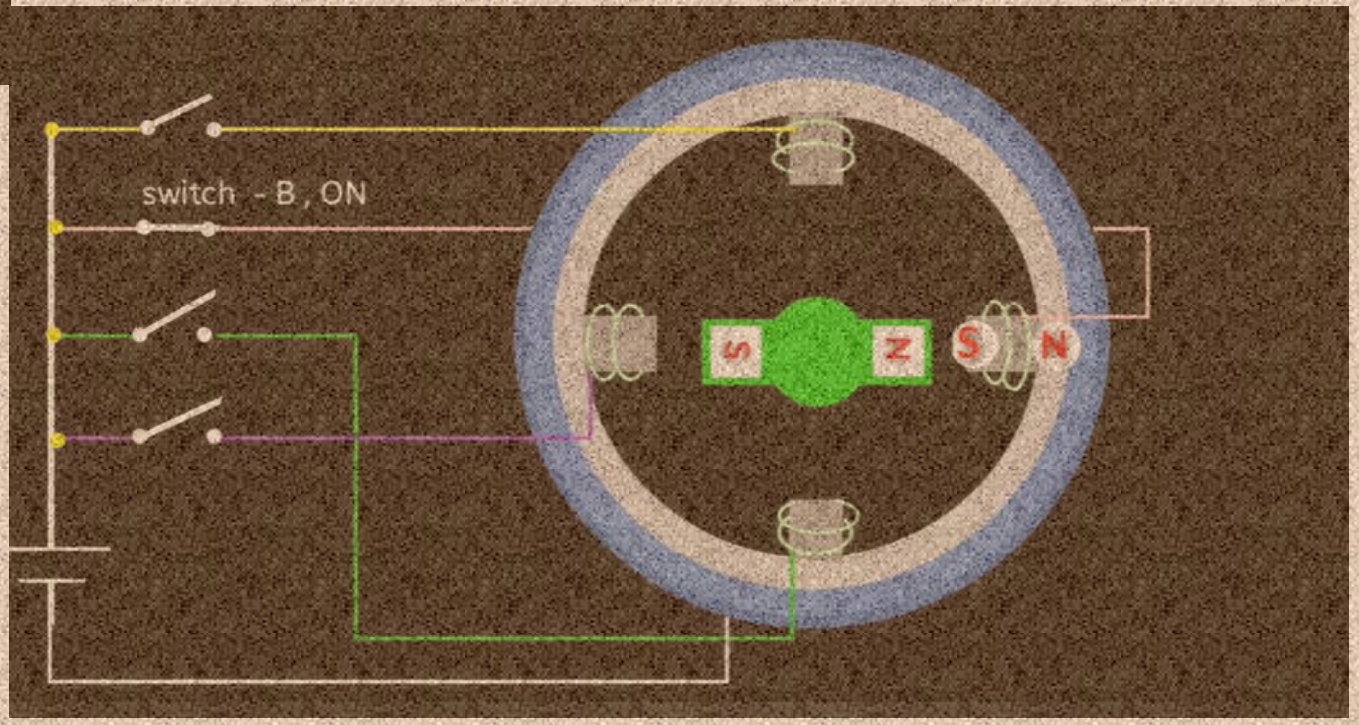
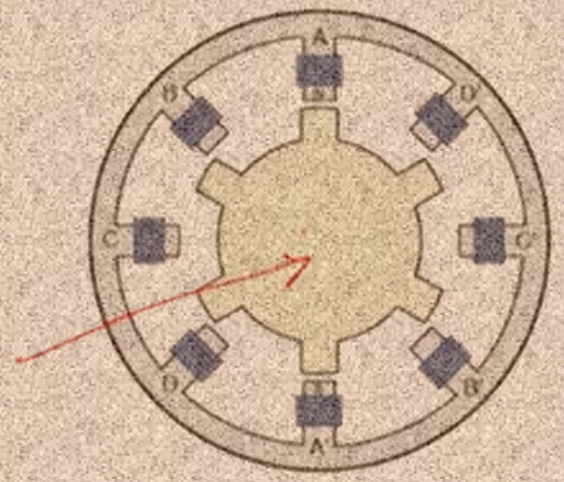
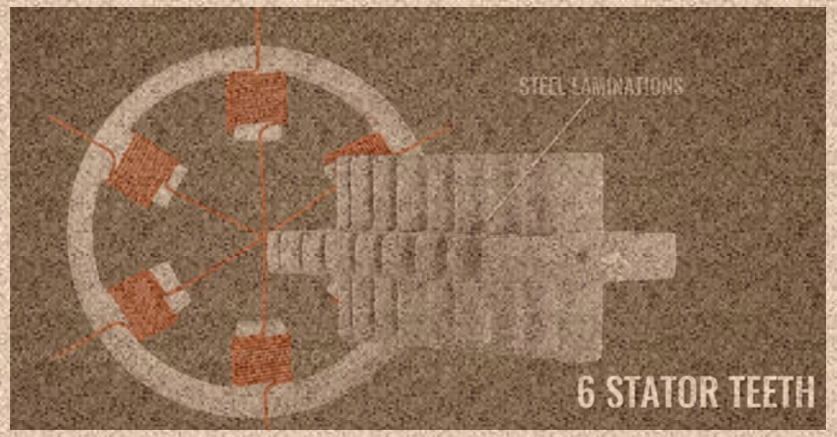
N
S


switch - B , ON
S
N
S
N

- The variable reluctance stepper motor has ferromagnetic rotor rather than the permanent magnet rotor.
- Motion and holding results from the attraction of stator and rotor poles to position with minimum magnetic reluctance that allow for maximum magnetic flux.

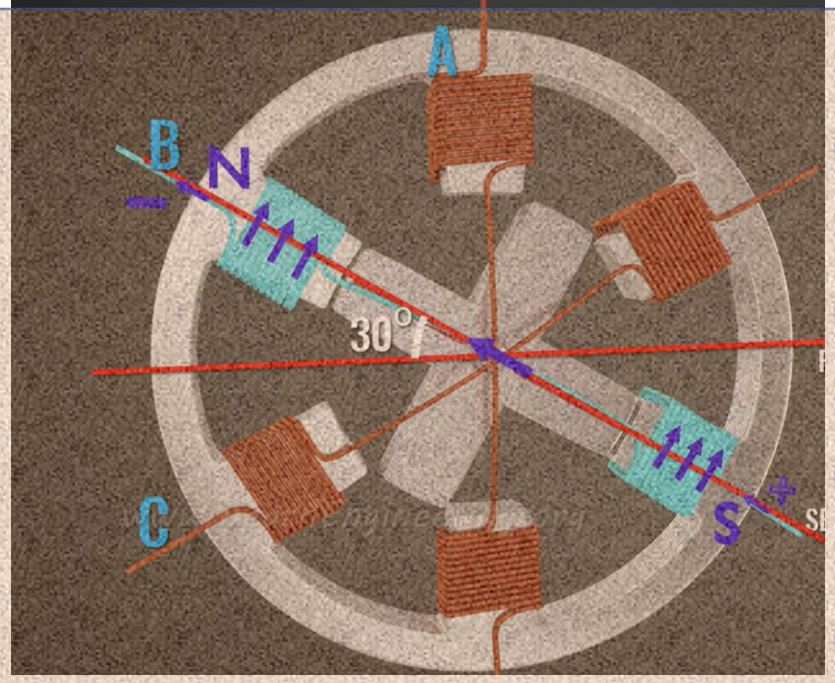


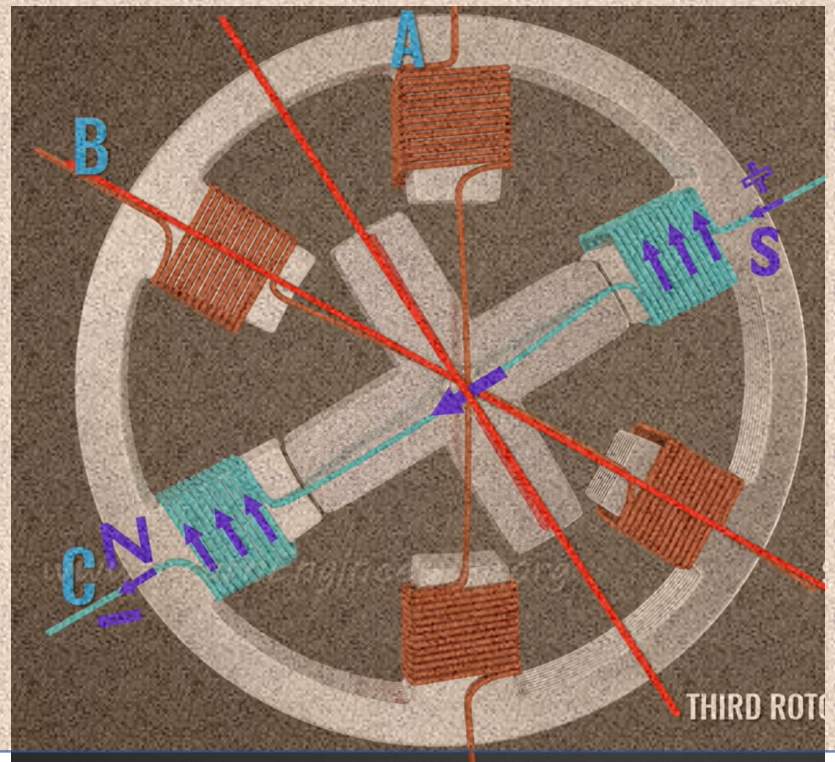
Variable reluctance stepper motor

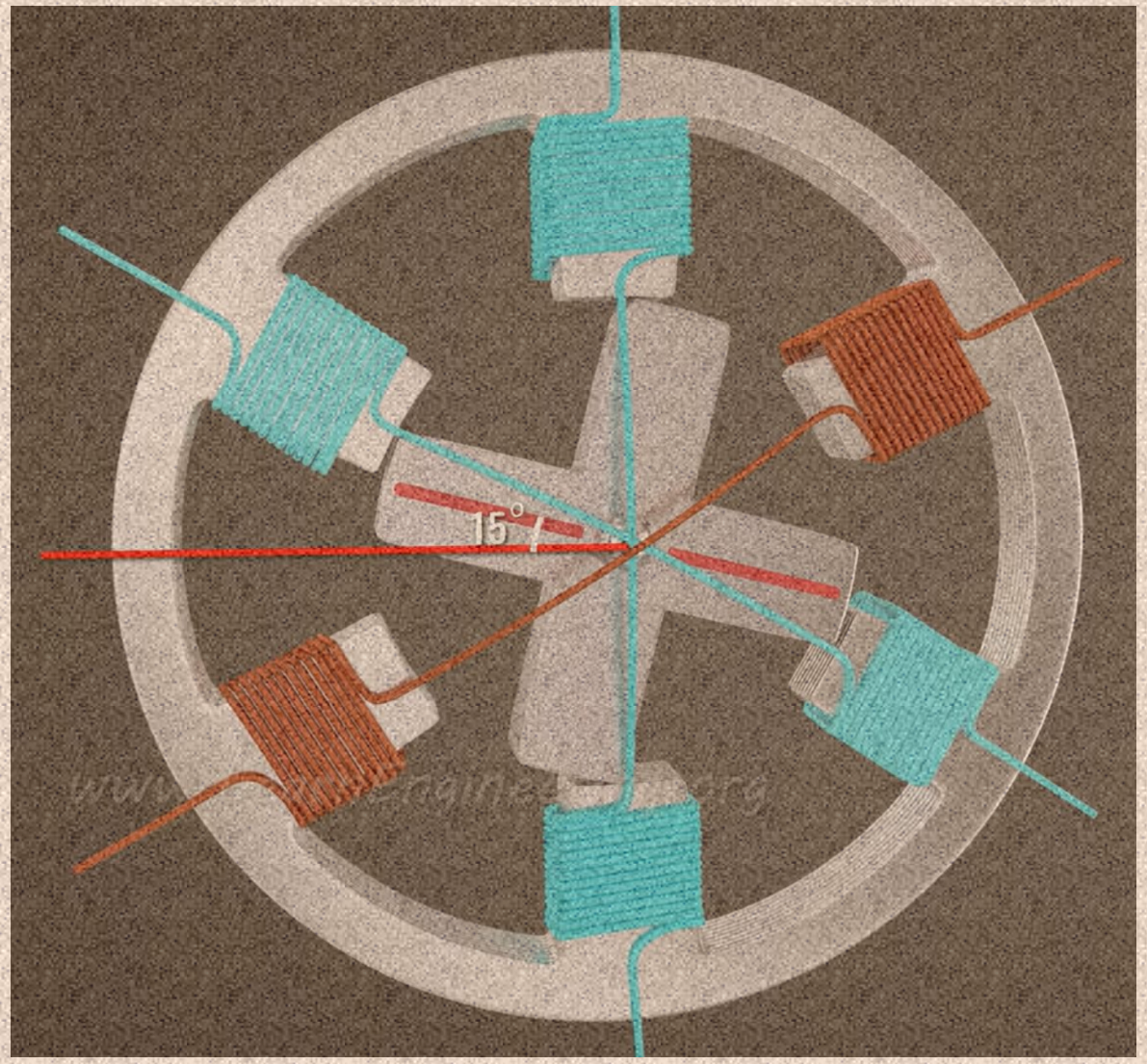


Stepper Motor Specifications

- Phase—Number of independent windings in the stator.
- Step angle—Rotor rotation for one switching change for stator coils.
- Holding torque—Maximum torque that can be applied to a powered motor without moving it from its rest position and reversing spindle rotation.



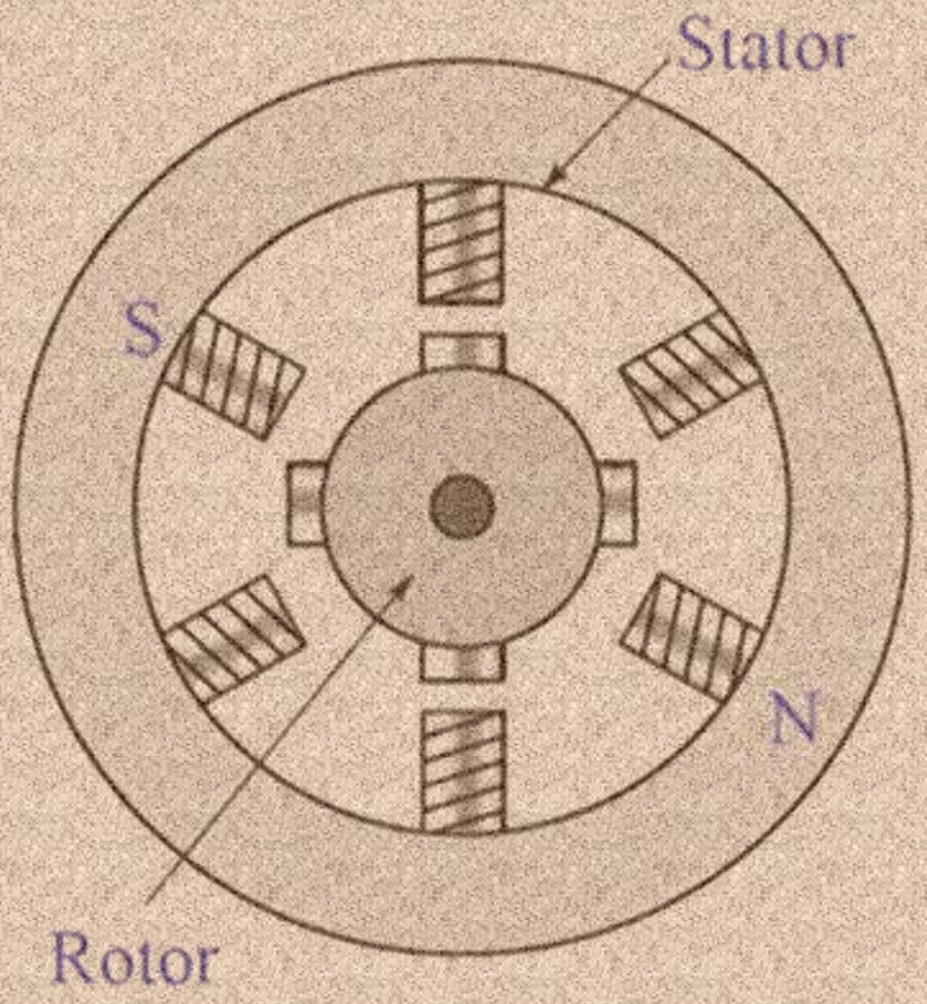




Half Stepping

Variable Reluctance Stepper Motor

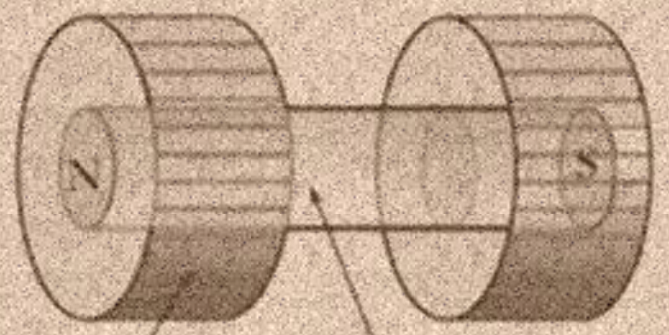
- In this motor the rotor is made of soft steel and is cylindrical with four poles, i.e. less number of poles than on the stator.
- When an opposite pair of windings has current switched to them, a magnetic field is produced with lines of force which pass from the stator poles through the nearest set of poles on the rotor.



(1)

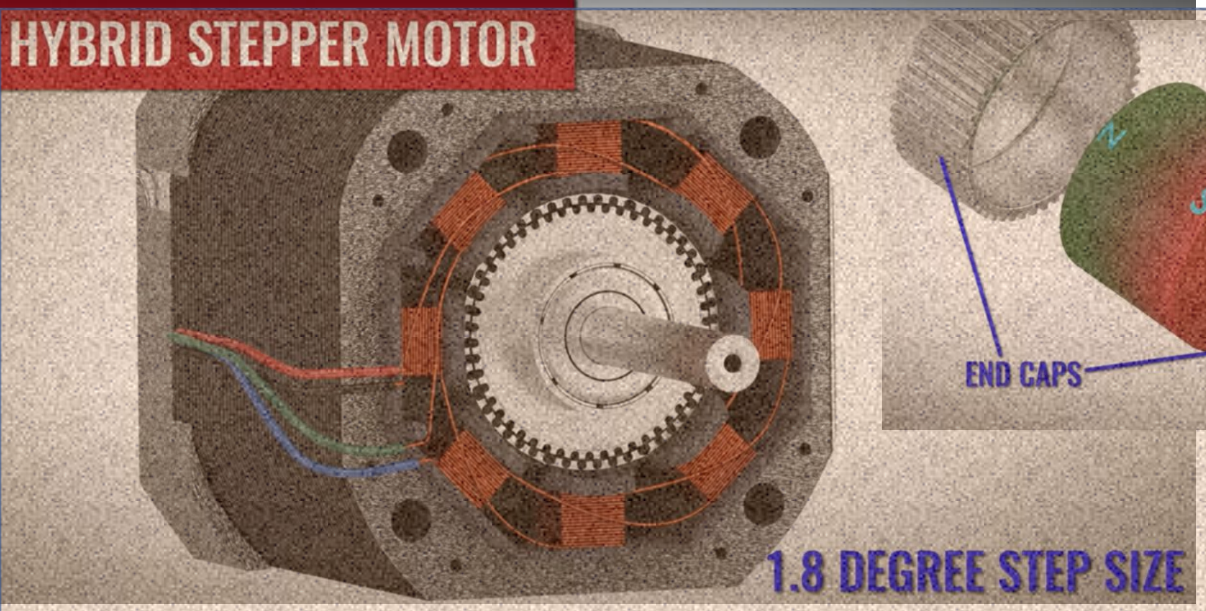
Hybrid Stepper

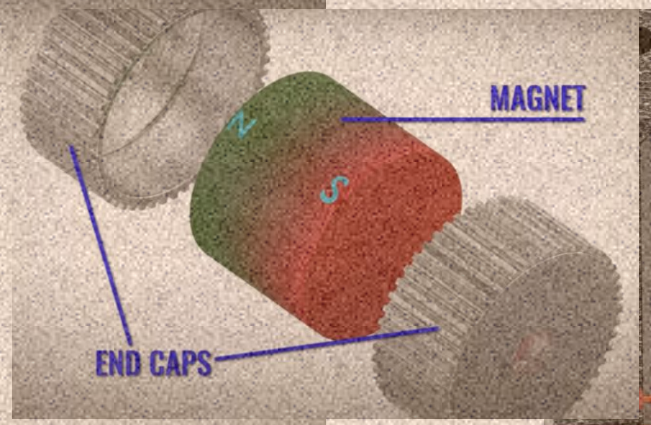
- Hybrid stepper motors combine the features of both the variable reluctance and permanent magnet motors, having a permanent magnet encased in iron caps which are cut to have teeth.
- The rotor sets itself in the minimum reluctance position in response to a pair of stator coils being energised.
- Used in computer hard disc drive.

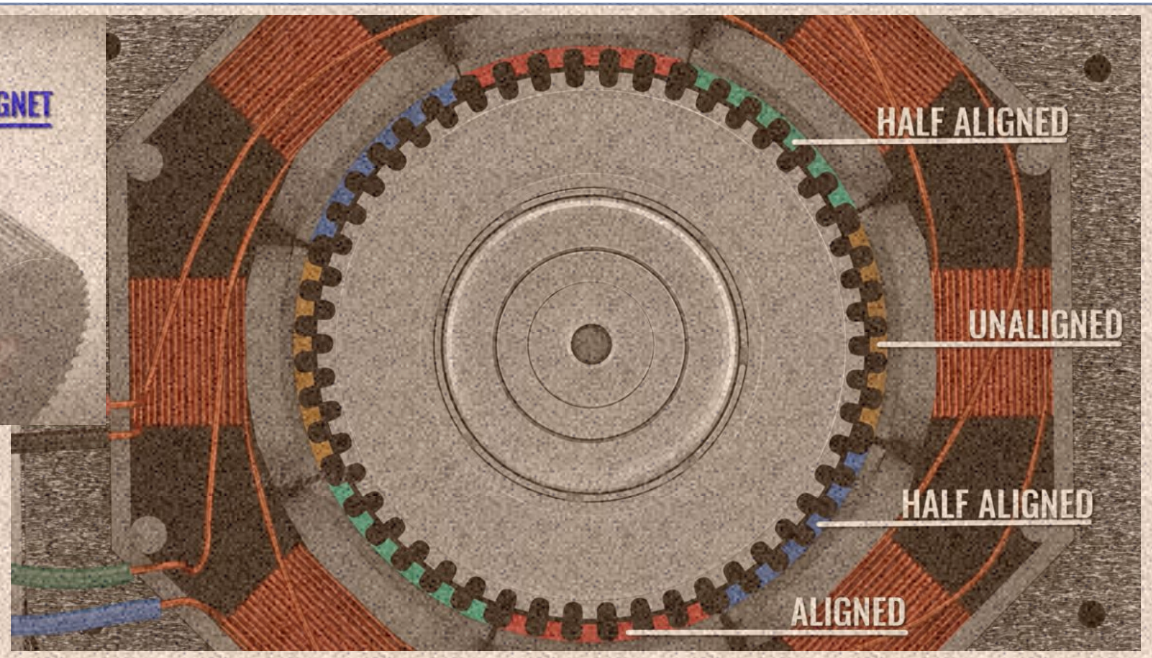


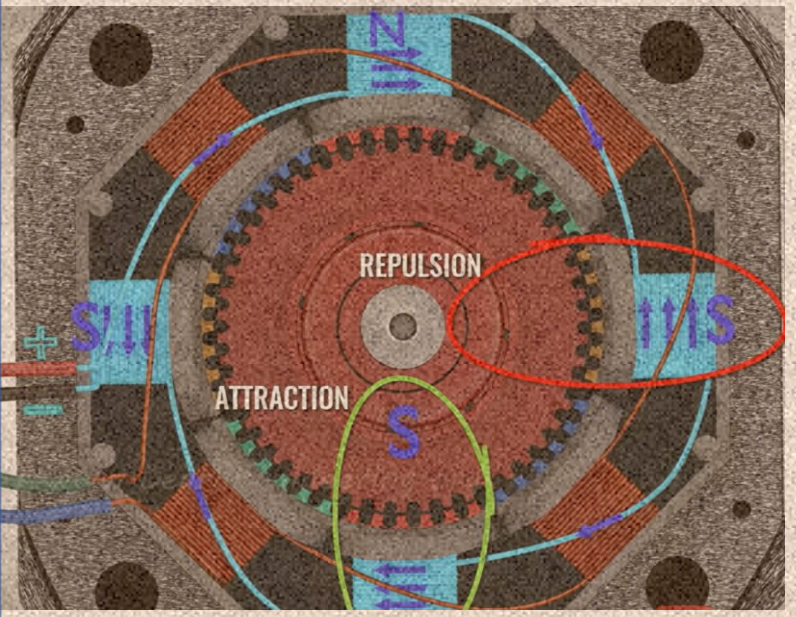
Teeth on end caps Permanent magnet

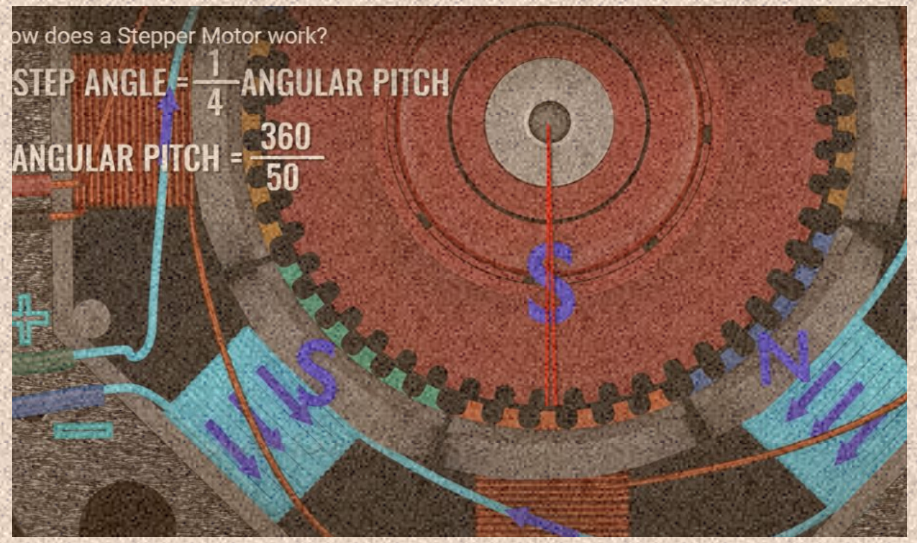
HYBRID STEPPER MOTOR

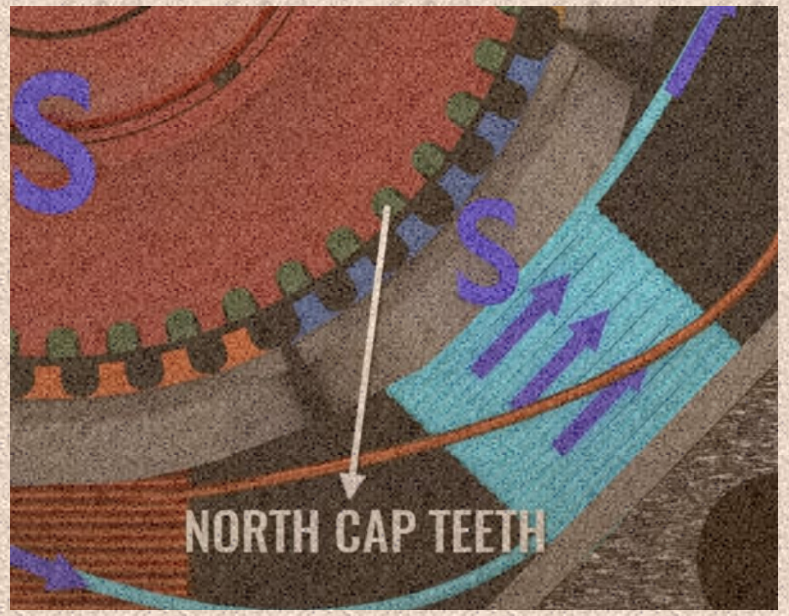




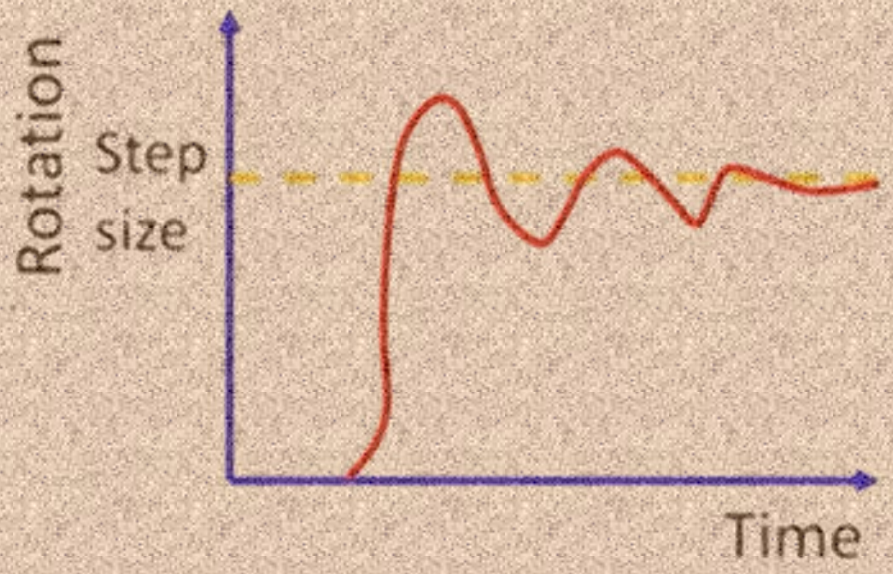


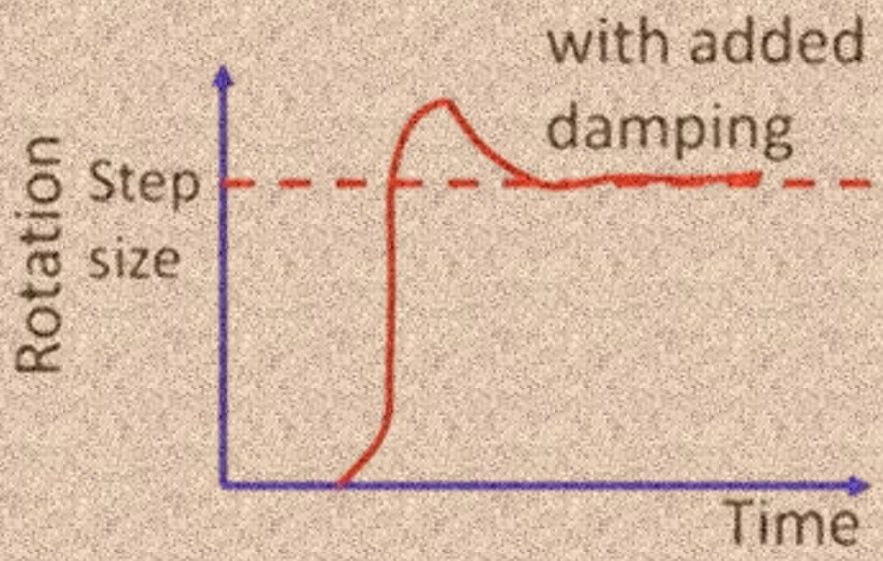






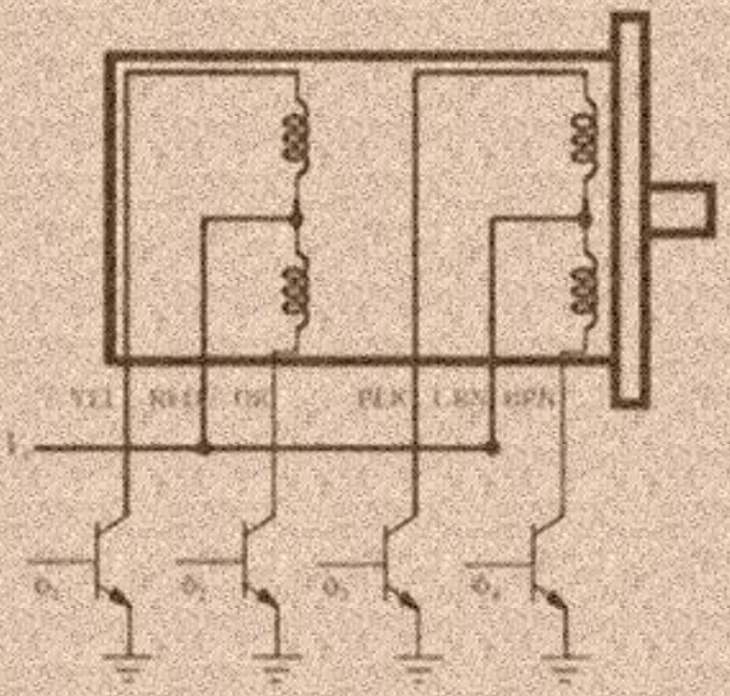
Dynamic Response of a Single Step

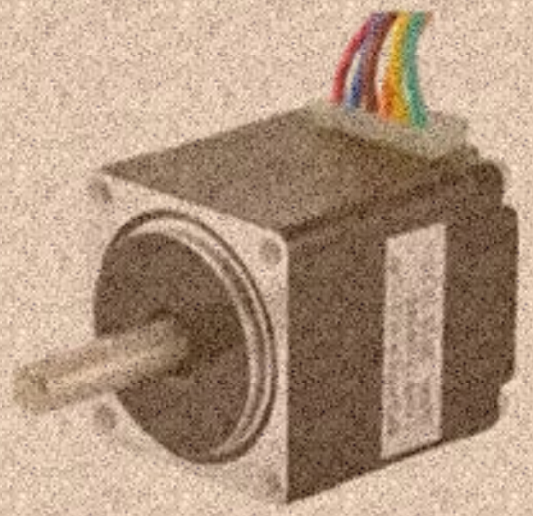




- A stepper motor driving a mechanical system through one step will exhibit an under damped response.
- If damping can be increased in the system by mechanical friction or viscous damping the response can be modified to reduce oscillations.

- Figure shows unipolar stepper motor field coil schematic with external power transistors that must be switched on and off to produce the controlled sequence of stator polarities to cause rotation.
- The schematic shows six wires connected to the motor.



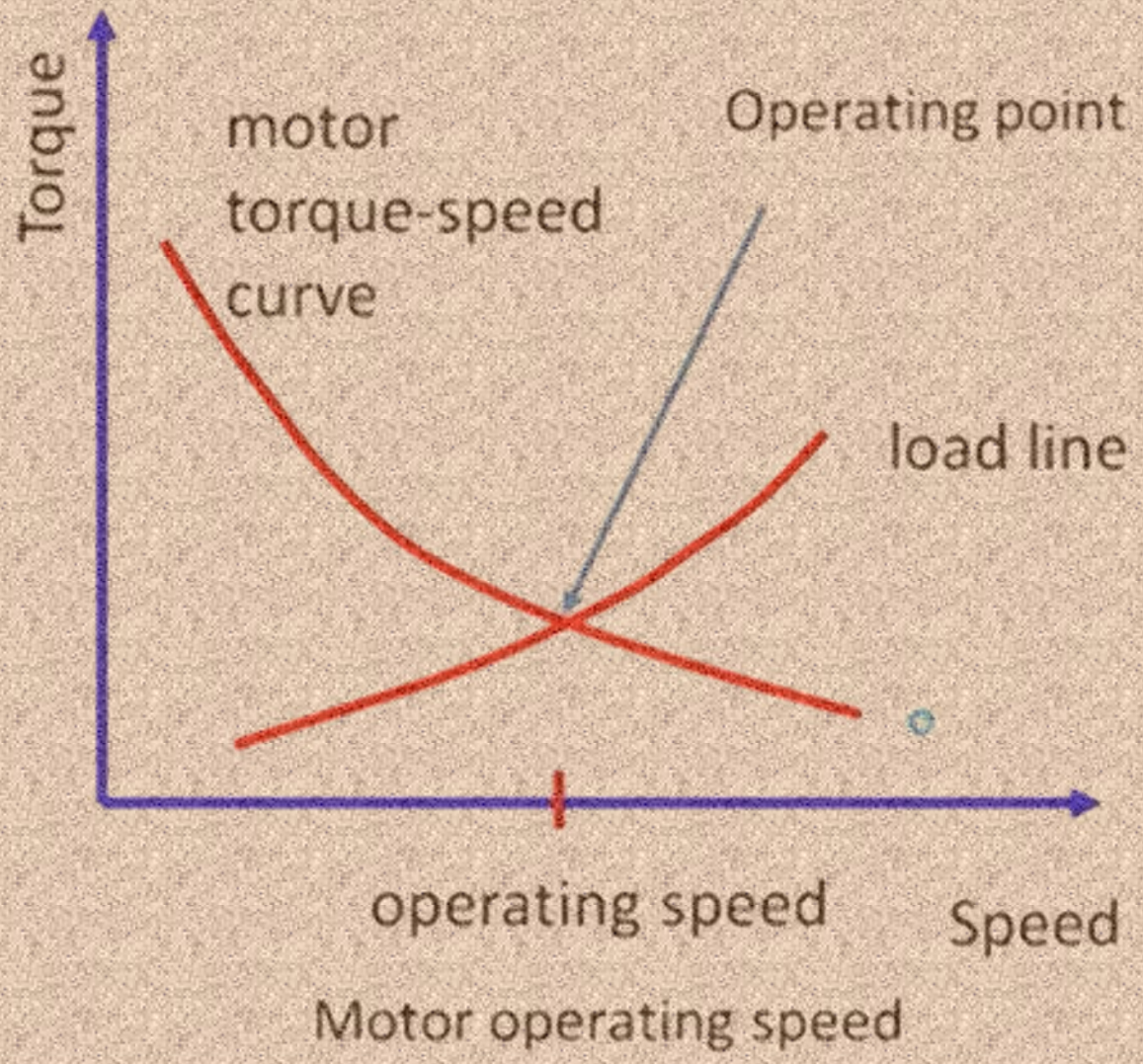


- Because the second and fifth wires are usually connected externally as shown, manufacturers sometimes connect them inside the motor, in which case the motor only has five external wires.
- The wires are usually color coded by the manufacturers to help the user make a correspondence to the schematic.
- Figure includes a common color scheme used for a six-wire unipolar.
- stepper motor: yellow (coil 1), red (1/2 common), orange (coil 2), black (coil 3), green (3/4 common), brown (coil 4).
- The most common commercially available stepper motors have 200 steps/rev in full step mode and are some time referred as 1.8° (360/200) stepper.

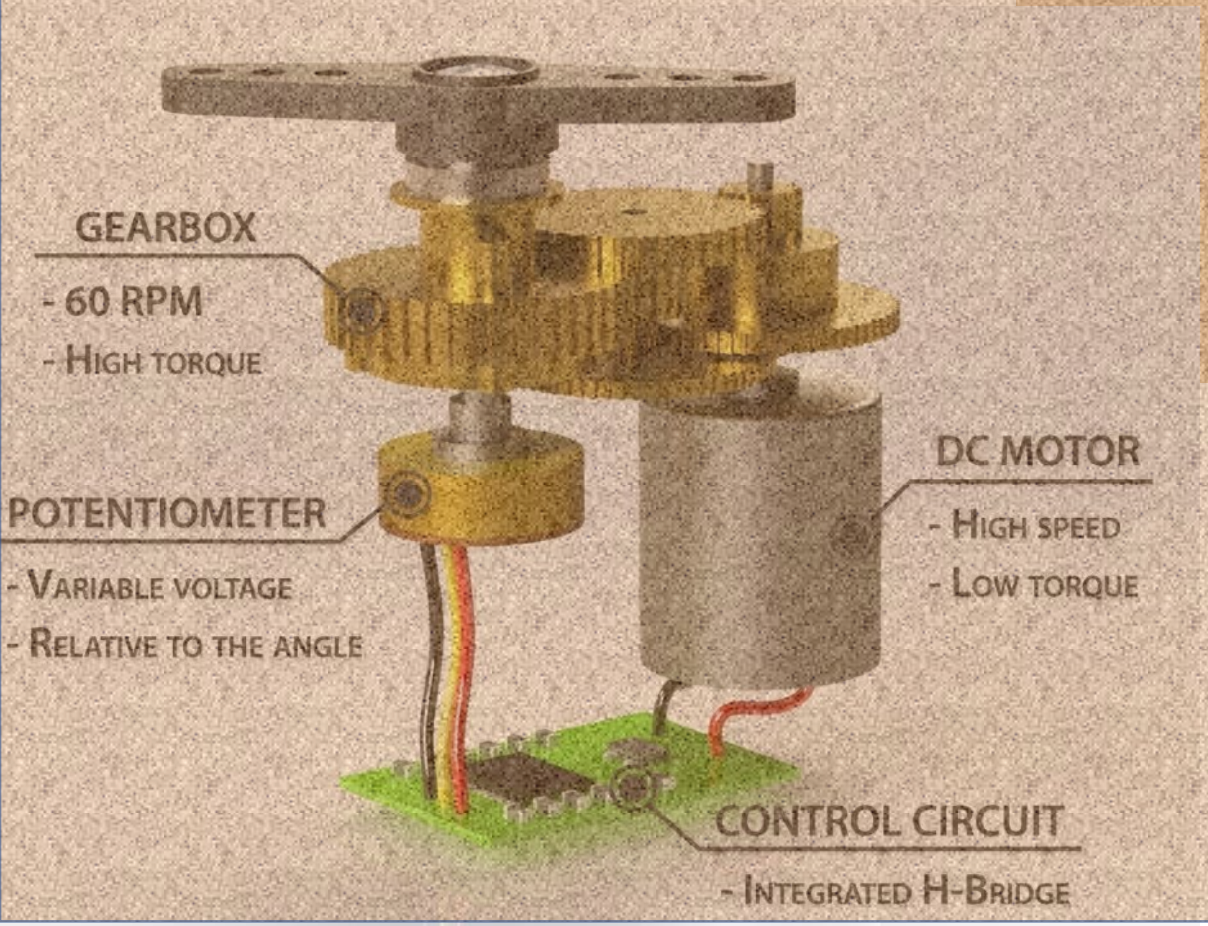
Selecting a Motor

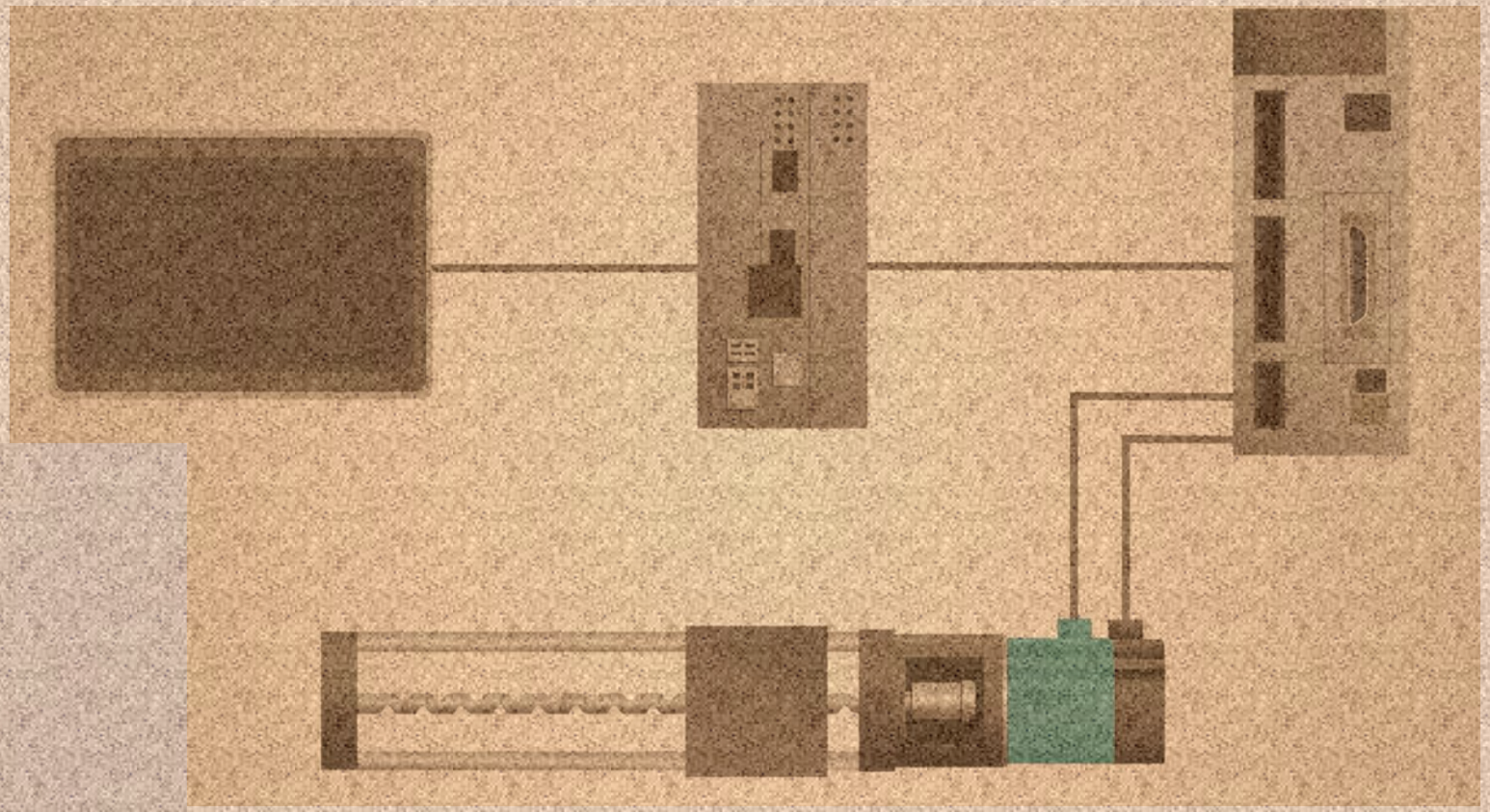
- When selecting a motor for a specific mechatronics application, the designer must consider many factors as
  - speed range,
  - torque-speed variations,
  - reversibility,
  - operating duty cycle,
  - starting torque,
  - power required

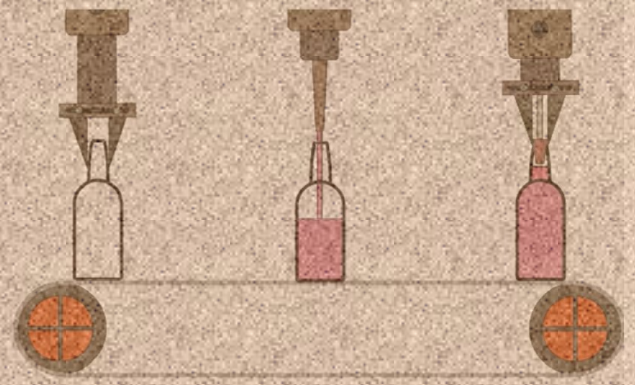
- For a given motor torque-speed curve and a well-defined load line, the system settles at a fixed speed operating point.
- Furthermore, the operating point is self-regulating.



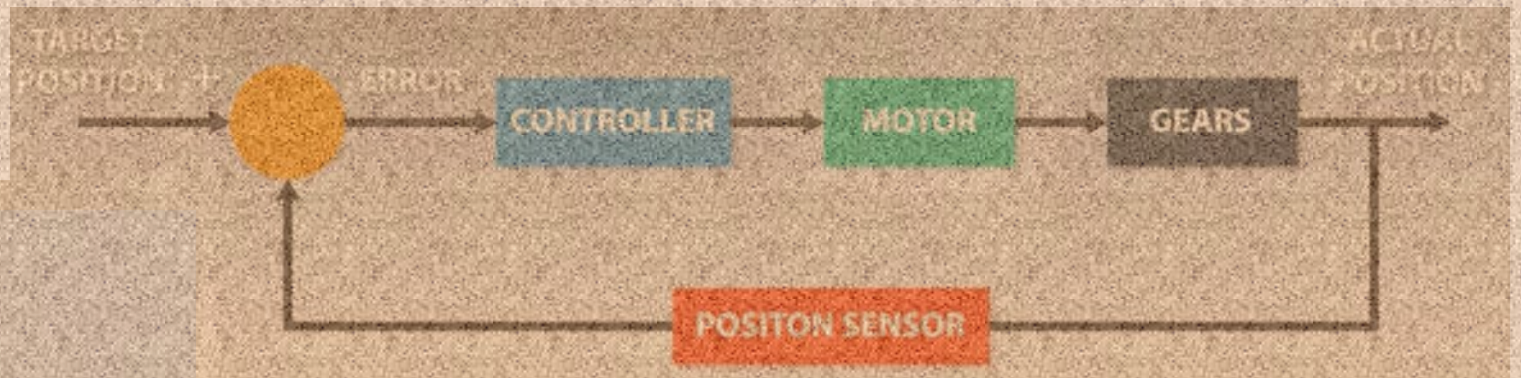
Servo Motors

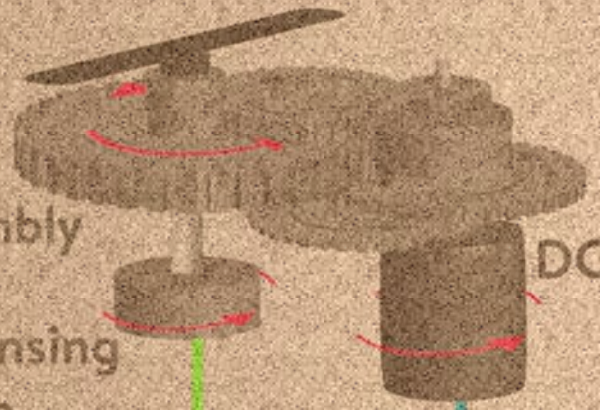


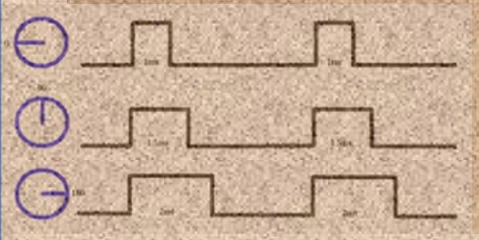


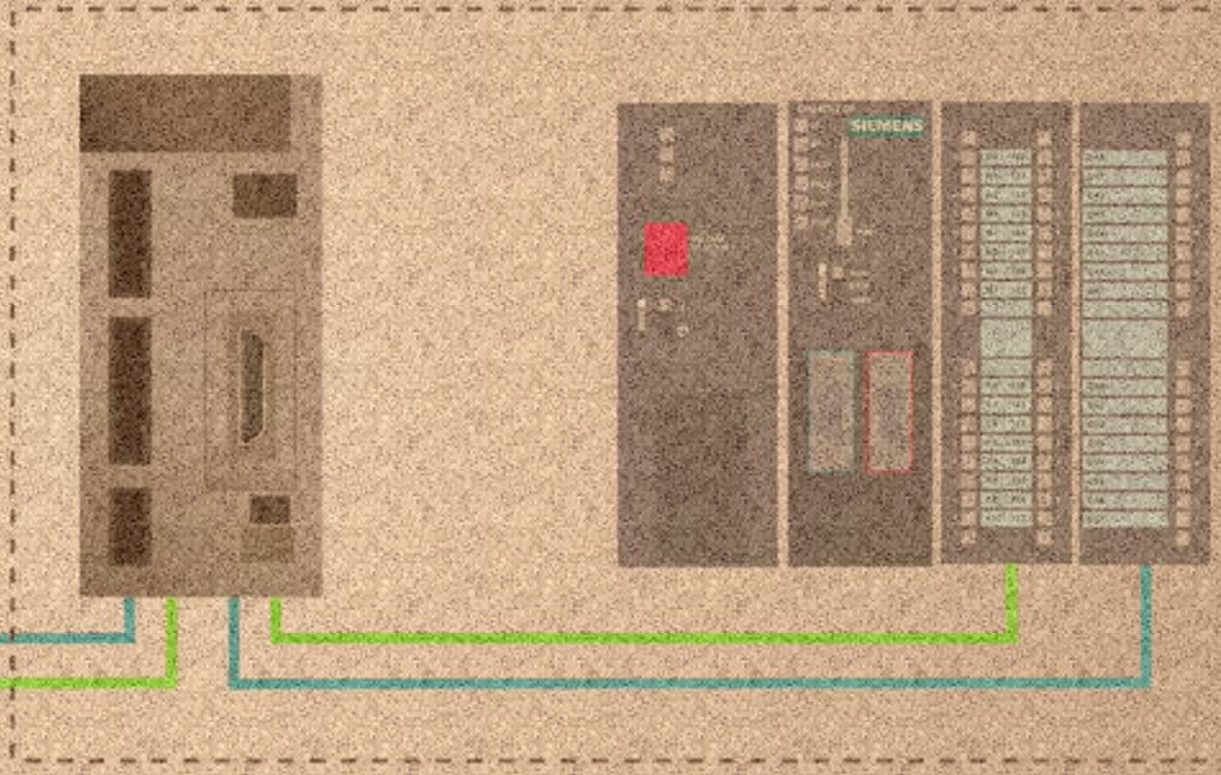


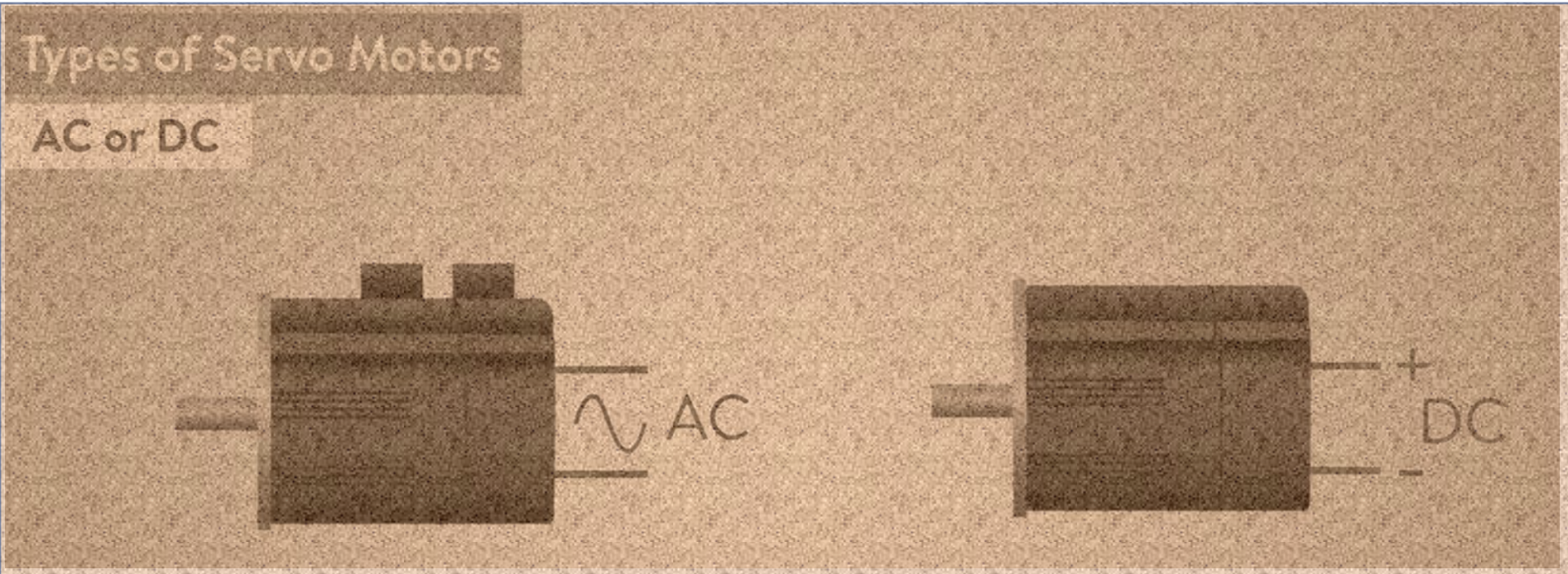
Working Principles of a DC Servo Motor



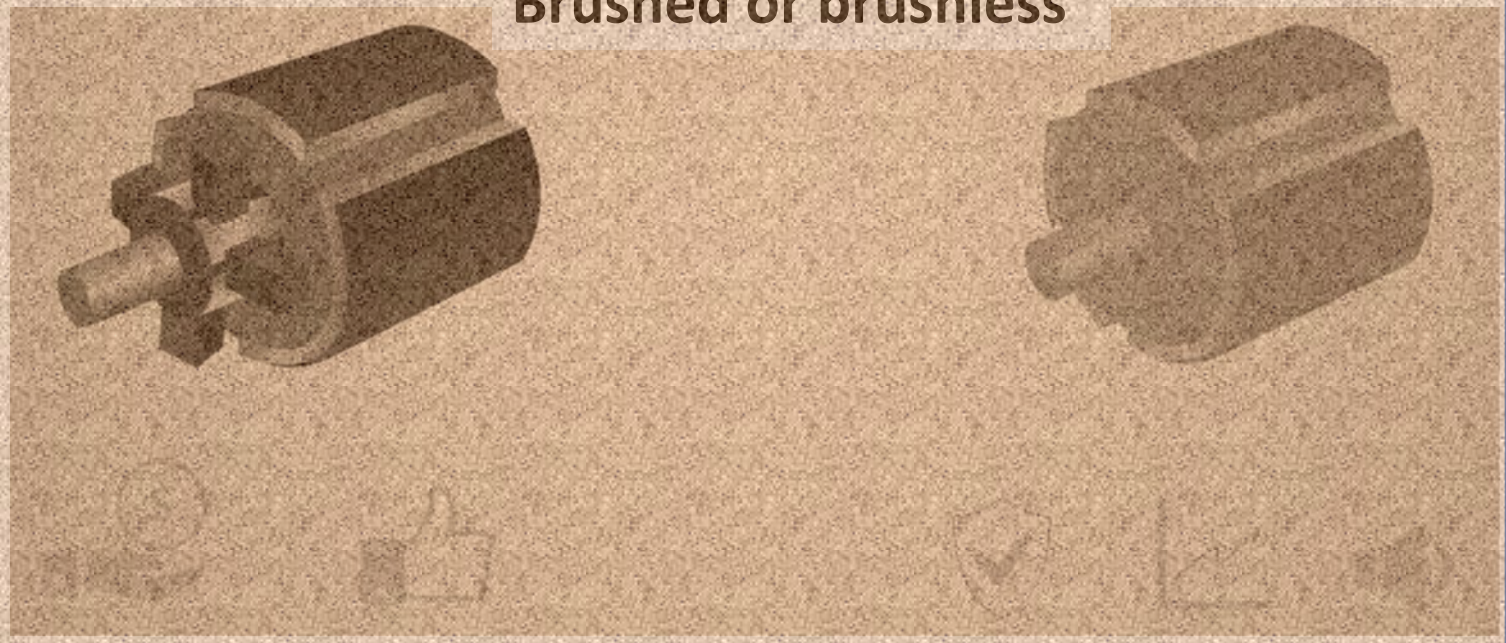
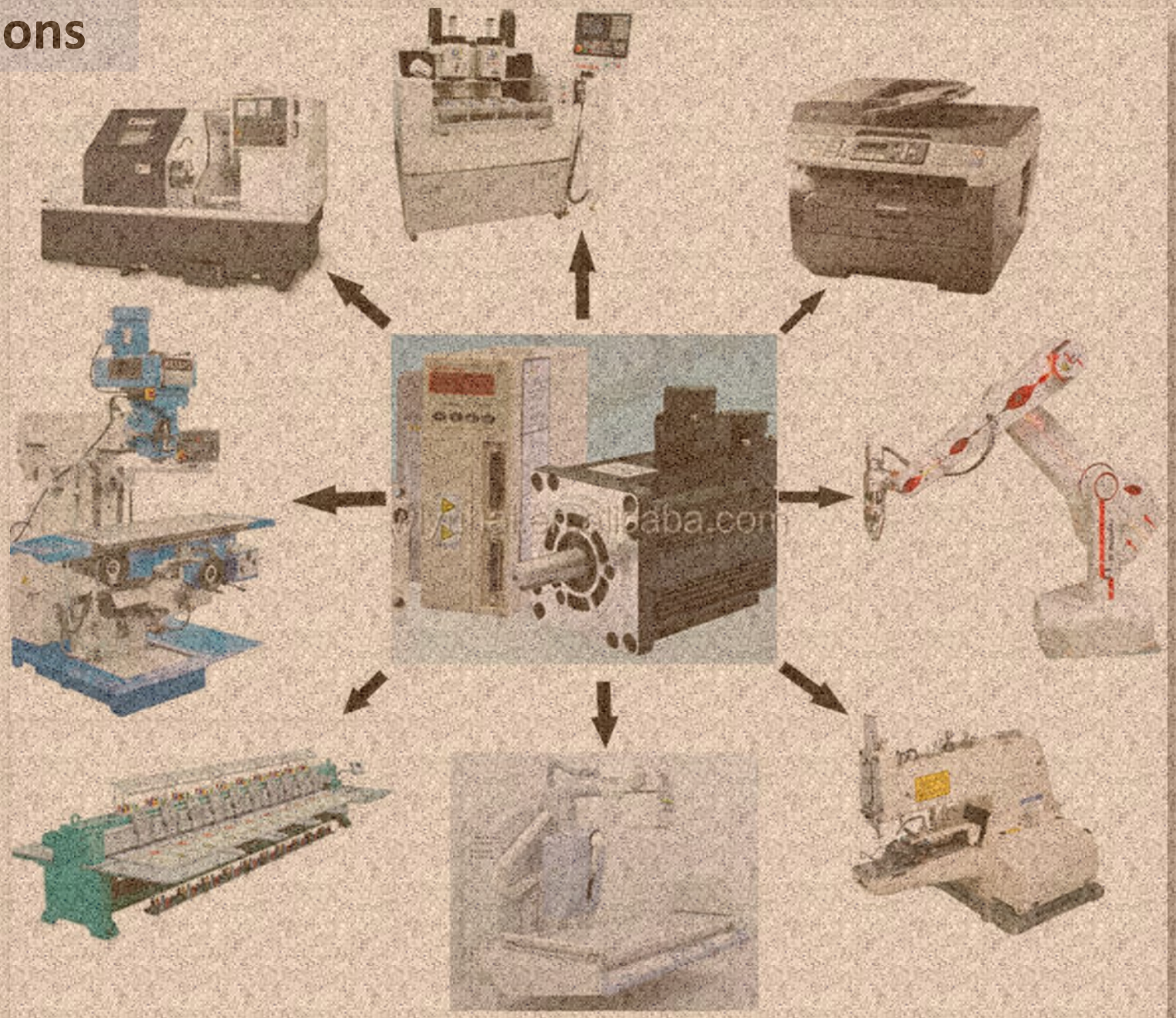







Types of Servo Motors
AC or DC
AC
+
DC
-

Types of Servo Motors


Brushed or brushless

Servo motor applications