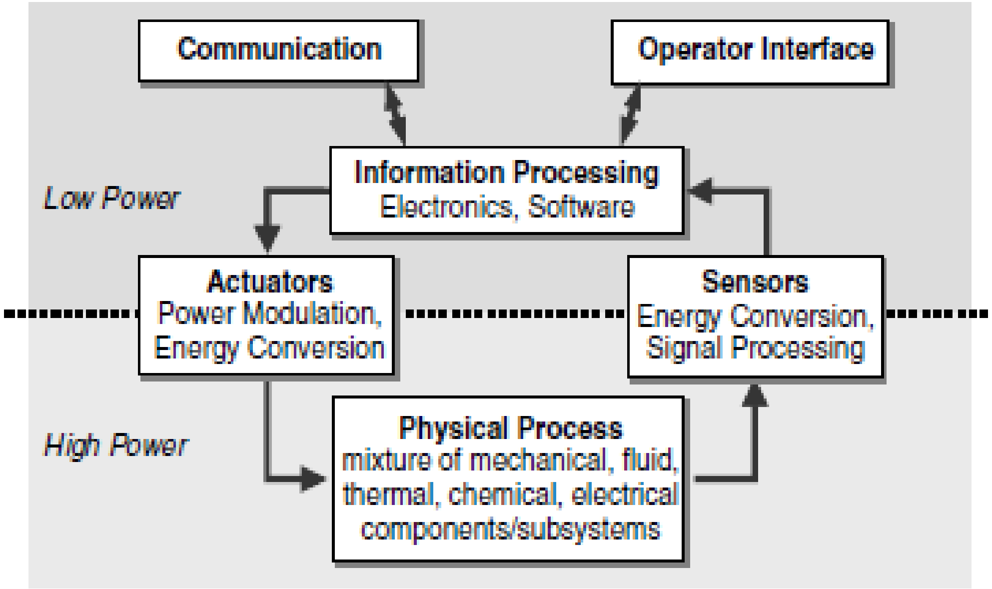
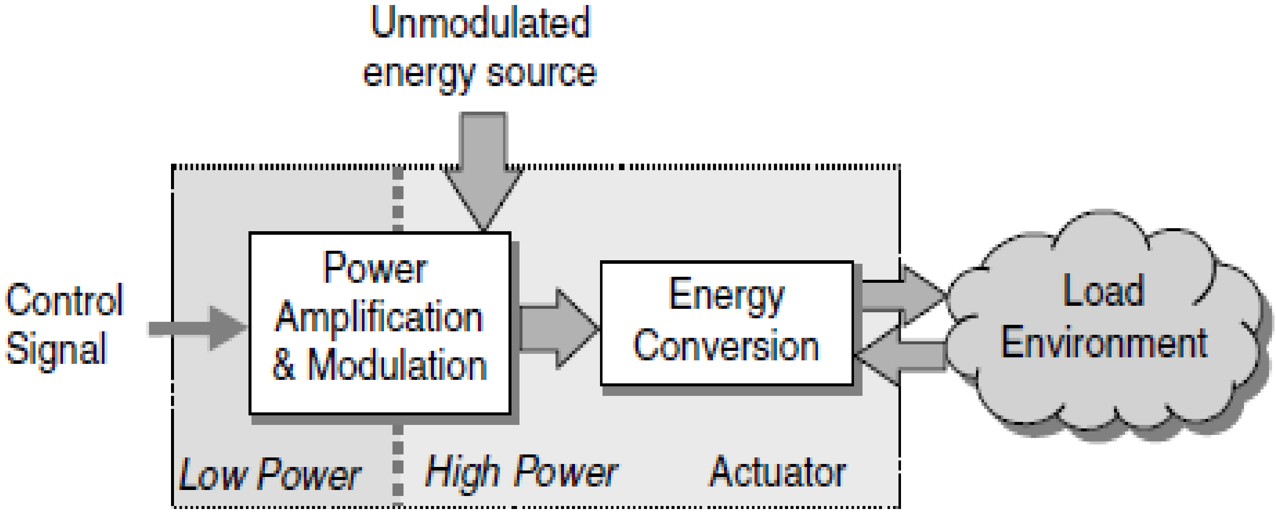
Actuators

- A device for moving or controlling something.
- Higher power region interacts with the physical world while lower energy region processes data.

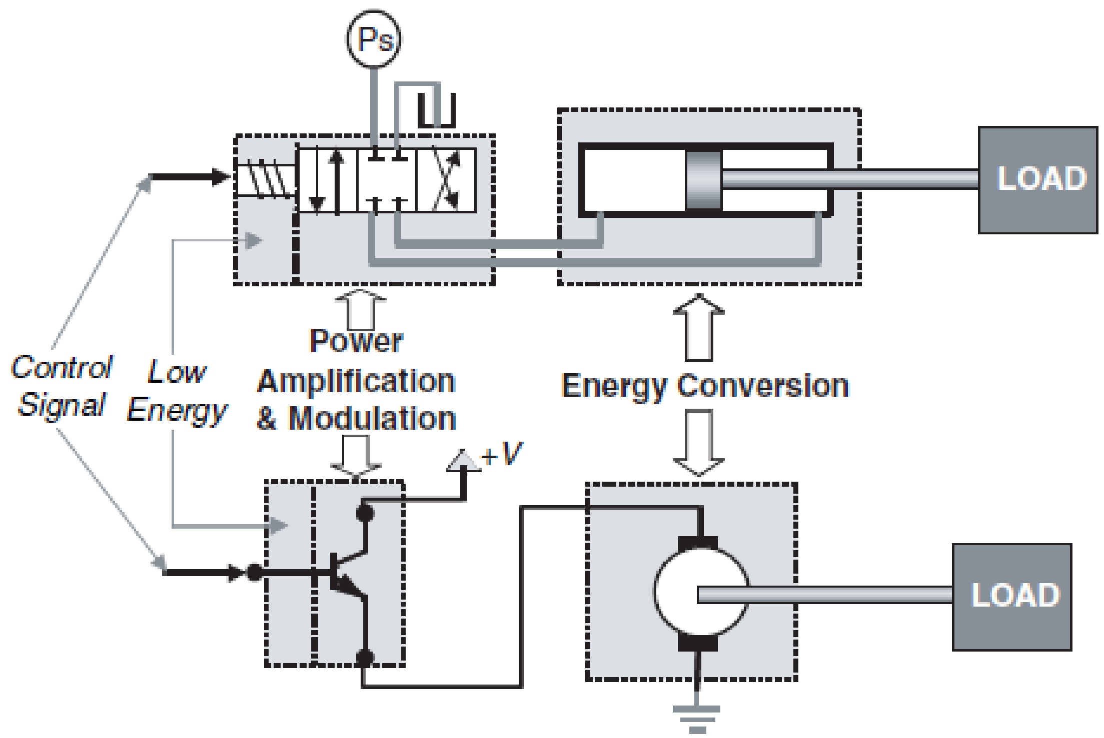


Functional diagram of actuator

- Actuators along with sensors achieve energy modulation and conversion



Functional diagram of electro hydraulic and electro mechanical Actuators



Electromagnetic Actuators

- Widely used.
- Magnetic field has higher energy density than electric.
- Energy per unit volume of air gap is five times more in magnetic field than electric.
- Fundamental principles – Faraday s law of EM induction and Lorentz law of EM forces.

Lorentz Law

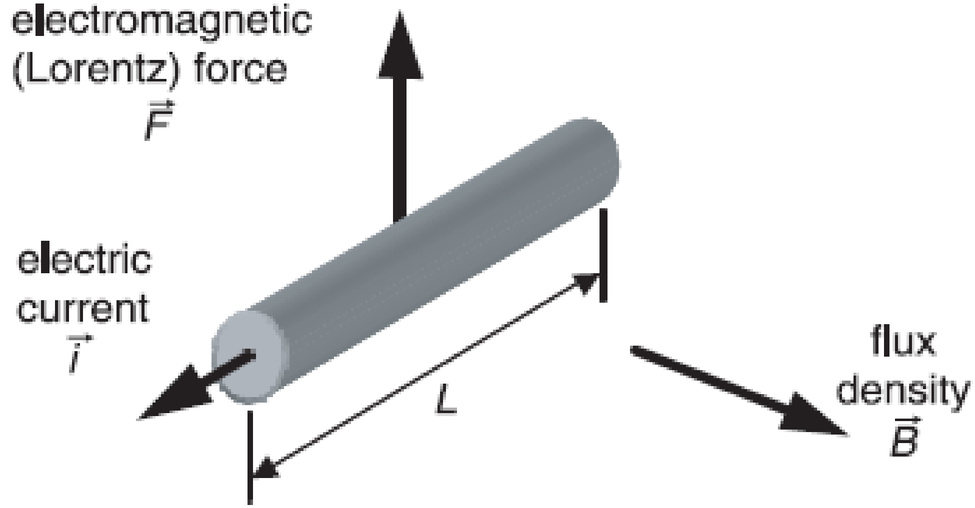
- If B is magnetic flux density (Tesla) and H is the magnetic field strength (A/m)

$$\vec{B} = \mu_r(\vec{H}) \cdot \mu_0 \cdot \vec{H}$$

- Induced force on a current carrying conductor in a magnetic field is

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

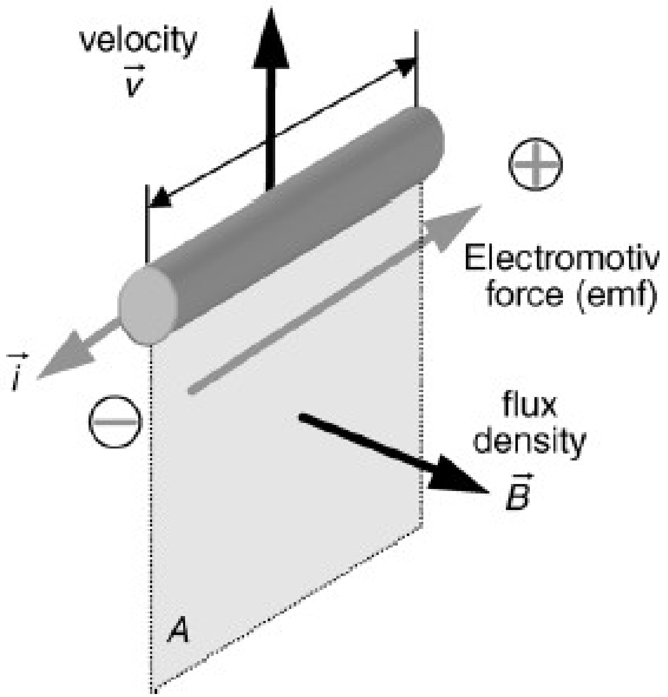
Lorentz Law



$$F = |\vec{F}| = BLi$$

Faraday s Law

- Motion of a conductor will produce emf as given by



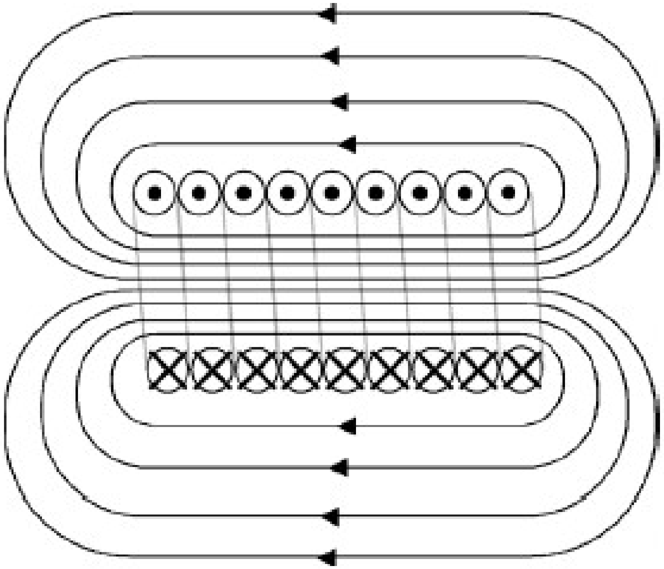
$$\text{emf} = E = -\frac{d\phi}{dt}$$

$$\text{emf} = E = BLv$$

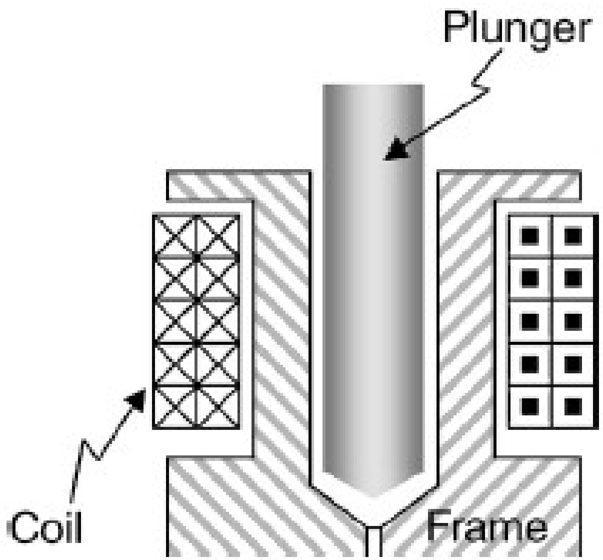
Solenoids

- The flux density in a helical coil with length L and N turns is given by
- The magnetic field can be increased by inserting a magnetic core or increasing permeability

$$B = \mu \frac{N}{L} \cdot i$$



Solenoids



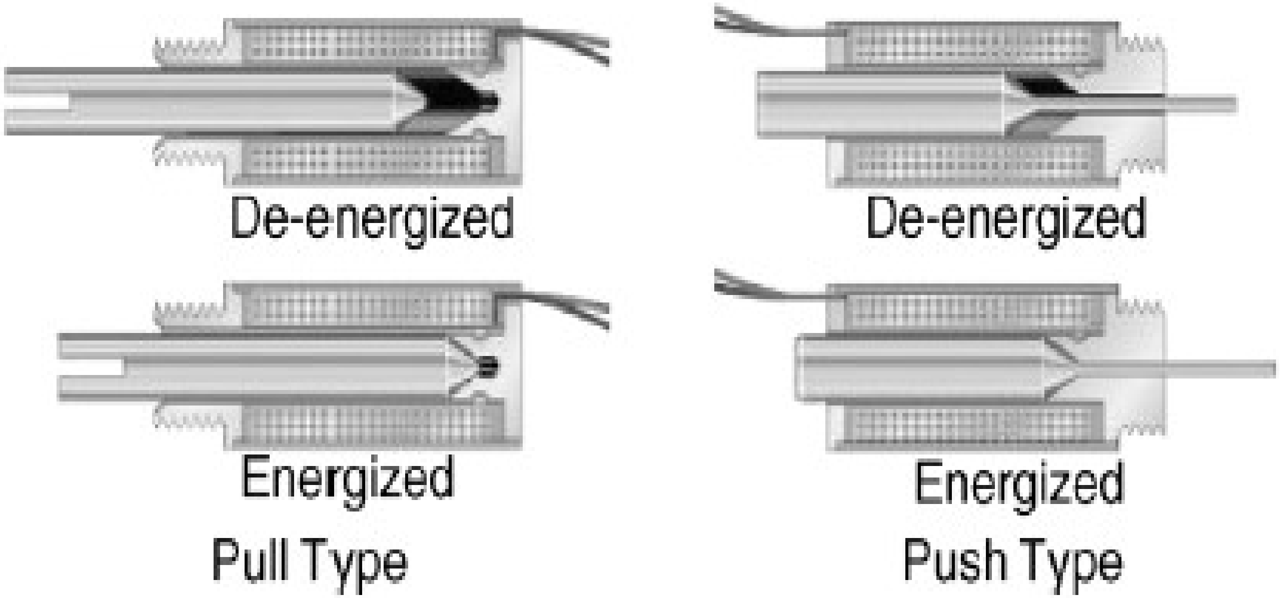
Solenoids

- Simplest electromagnetic devices
- Used for linear and rotary actuation of valves, relays and switches.
- As coil is energized B is produce in the coil. The plunger moves down to reduce the air gap. Magnetic force generated is given by

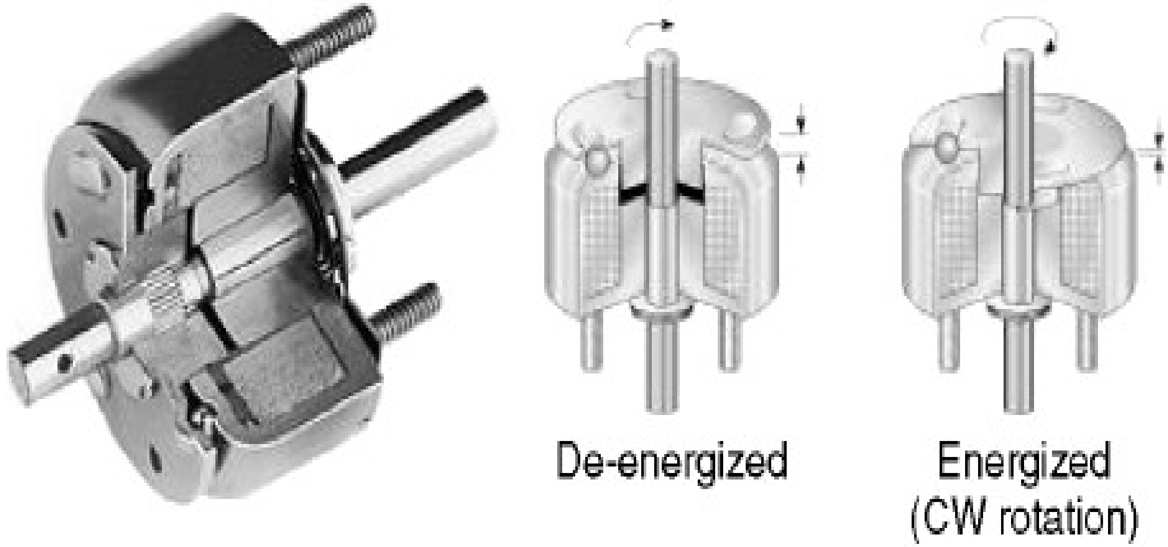
$$F \propto \frac{i^2}{\delta^2}$$

- In any solenoid the Force ca creased by using better magnetic material, increase N and or L and D.

Types of Solenoids

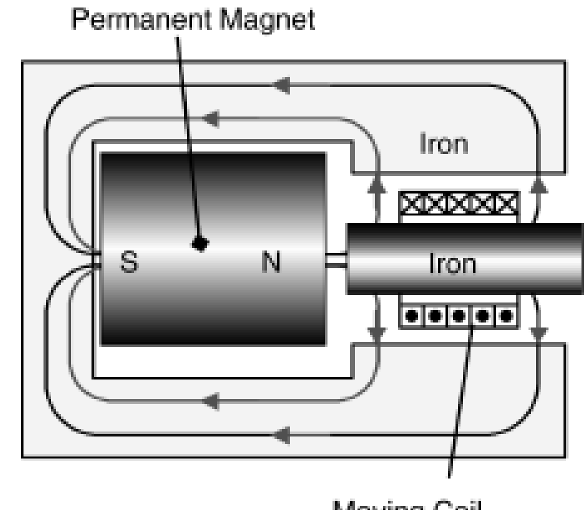


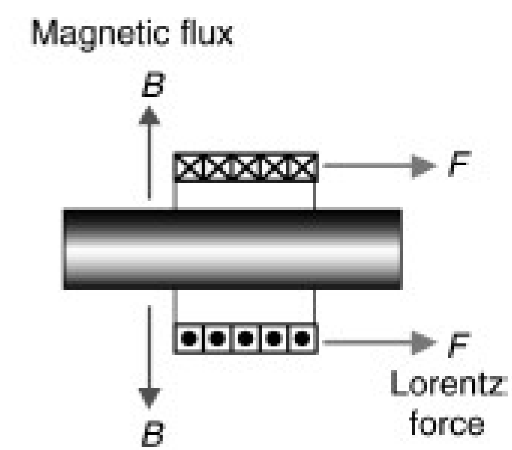
Types of Solenoids



Applications

- Voice Coil Motor
- Developed for loudspeakers. Used in r/w head in HDDs.
- Moving coil type actuator. Coil is suspended in the air gap by springs
- Connected to diaphragm, spool or head.
- Linear F and I relation, Bidirectional.
- Closed loop control needed.



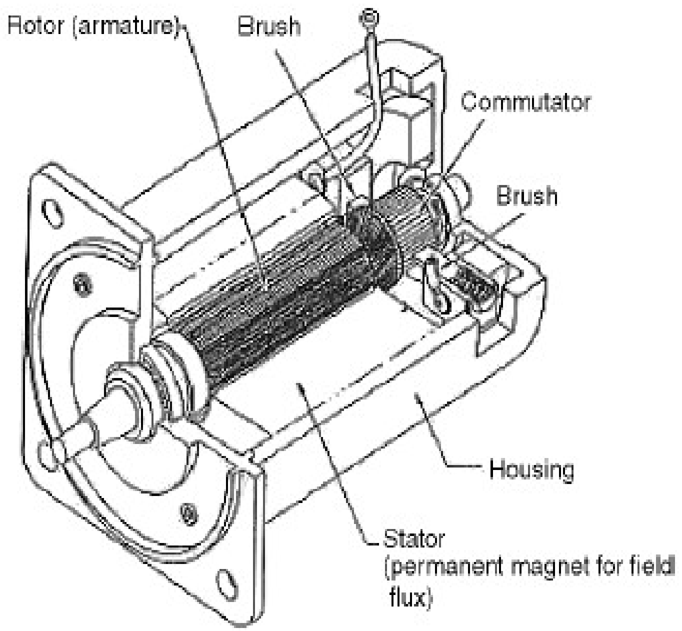


Electric Motors

- A typical electric motor consists of
- Stator – Generates magnetic flux. Permanent magnet coil windings
- Coil – generates magnetic field
- Rotor – permanent magnet or FM core with coil windings (armature)
- Armature – carries winding and induces
- Brush – Part of DC motor through which current is supplied

Electric Motors

- Commutator – In contact with brushes and controls current direction



Classification

Classification			
Command Input	Magnetic Field		Description
DC motors	Permanent magnet		Permanent magnets are used to generate the stator magnetic field. Electrical current is supplied directly into the armature winding of the rotor through the brushes and commutators.
	Electro-magnets	Shunt wound	A stator (field) winding is used as electromagnet. Stator winding is connected in parallel with the armature winding.
		Series wound	A stator (field) winding is used as electromagnet. Stator winding is connected in series with the armature winding.
		Compound wound	Two stator (field) windings are used as electromagnet. The stator windings are connected, one in series and one in parallel, with the armature winding.
		Separate wound	A stator (field) winding is used as electromagnet. Both the stator and armature fields are individually energized.

Classification

AC motors	Single-phase	Induction	Single stator winding with squirrel-cage rotor. No external connection to the rotor. Torque generation is based on the electromagnetic induction between the stator and rotor. AC current provides the commutation of the fields. Rotor speed is slightly slower than the rotating stator field (slip).
		Synchronous	Permanent magnet rotor or rotor winding with slip ring commutation. Rotating speed is synchronized with the frequency of the AC source.
	Poly-phase	Induction	Similar to single-phase induction motor but with multiple stator windings. Self-starting.
		Synchronous	Similar to single-phase synchronous motor but with multiple stator windings for smoother operation.
	Universal		Essentially a single-phase AC induction motor with similar electrical connection as a *series wound* DC motor. Can be driven by either AC or DC source.

Classification

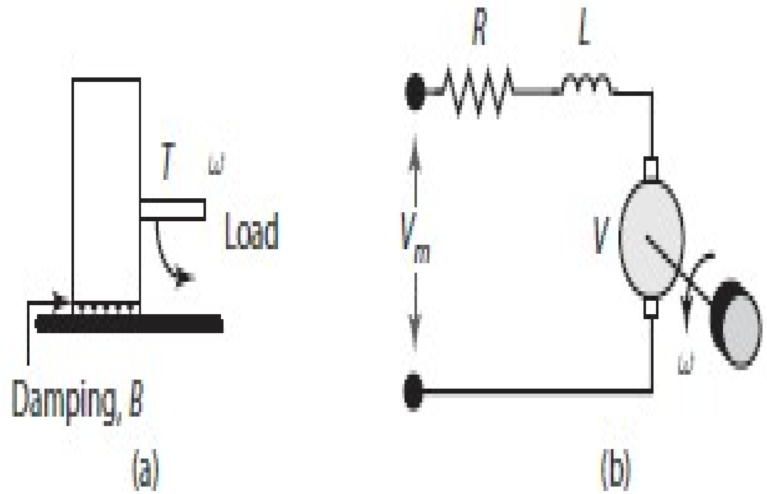
Stepper Motors	Permanent magnet		Permanent magnet rotor with stator windings to provide matching magnetic field. By applying different sequence (polarity) of coil current, the rotor PM field will align to match induced stator field.
	Variable reluctance		Teethed ferromagnetic rotor with stator windings. Rotor motion is the result of the minimization of the magnetic reluctance between the rotor and stator poles.
	Hybrid		Multi-toothed rotor with stator winding. The rotor consists of two identical teethed ferromagnetic armatures sandwiching a permanent magnetic.
Brushless DC motors	Poly-phase	Synchronous	Essentially a poly-phased AC synchronous motor but using electronic commutation to match rotor and stator magnetic fields. Electronic commutation enables using a DC source to drive the synchronous motor.

DC Motors

- Most popular
- Precise and continuous control of speed over wide range of operations by varying voltage.
- Easy to speed control over a wide range, speed-torque characteristics and high torque.
- Typically rotary actuators
- Can be powered by gen-sets, batteries or from the mains
- Power range from fraction of watt to several hundred KW.
- CNCs, industrial robots, servo valve actuators, manufacturing equipment.

DC motor operation

- Apply voltage to armature and the armature rotates in the magnetic field produce.
- Speed control is achieved by controlling armature voltage and magnetic field strength.
- Speed is proportional to voltage and torque is proportional to current.
- P = 2PiNT



Model of D.C Motor

The behaviour of DC motors can be explained by two fundamental equations. These equations are known as torque and voltage equations.

Torque equation: $T = k_t \text{ X } i$

Voltage equation: $V = k_e \text{ X } \Theta$

where

T is motor torque in N-m (newton-meters)

V is induced voltage in V (volts)

i is current in the armature circuit in A (amperes)

Θ is rotational displacement of the motor shaft in rad (radians)

K_t torque constant in Nm/A

K_t voltage constant in V/(rad/sec)

Problems with conventional D.C Motors

A major maintenance problem in conventional DC motors is brush arcing.
The magnetic polarity of the stator is fixed, and the polarity of the rotor is switched mechanically to get proper direction of motor torque.
The armature voltage is supplied by a pair of brushes that maintain contact with split slip-ring commutation.

Brushes are the weak factors in DC motors, and they generate excessive noise, contact bounce, and maintenance problems due to rapid wear out.

Brushless D.C. Motors

Brushless DC motors prevent brush arcing by putting the permanent magnet in the rotor and energizing the stator through angular positions.

Modern, brushless DC motors use solid-state switching for commutation. In these motors, electrical commutation duplicates mechanical brush commutation.

In brushless DC motors, the polarity of the rotor unit, which is a permanent magnet, is fixed relative to the rotor itself, and the polarity of the stator is switched by electronic means to achieve the same objective.

Since the electrical commutation simulates the mechanical commutation in conventional systems, brushless DC motors exhibit similar torque speed characteristics.

Brushless D.C Motors

The advantages of brushless DC motors are high reliability and the ability to generate relatively high torque at speeds up to 100,000 rpm.
Brushless DC motors are used in general-purpose applications, as well as in servo systems for motion control applications.
Motors in the range up to 1 HP and operating at speeds up to 7,200 rpm are used in computer peripherals and also are used as drivers for fluid power devices.

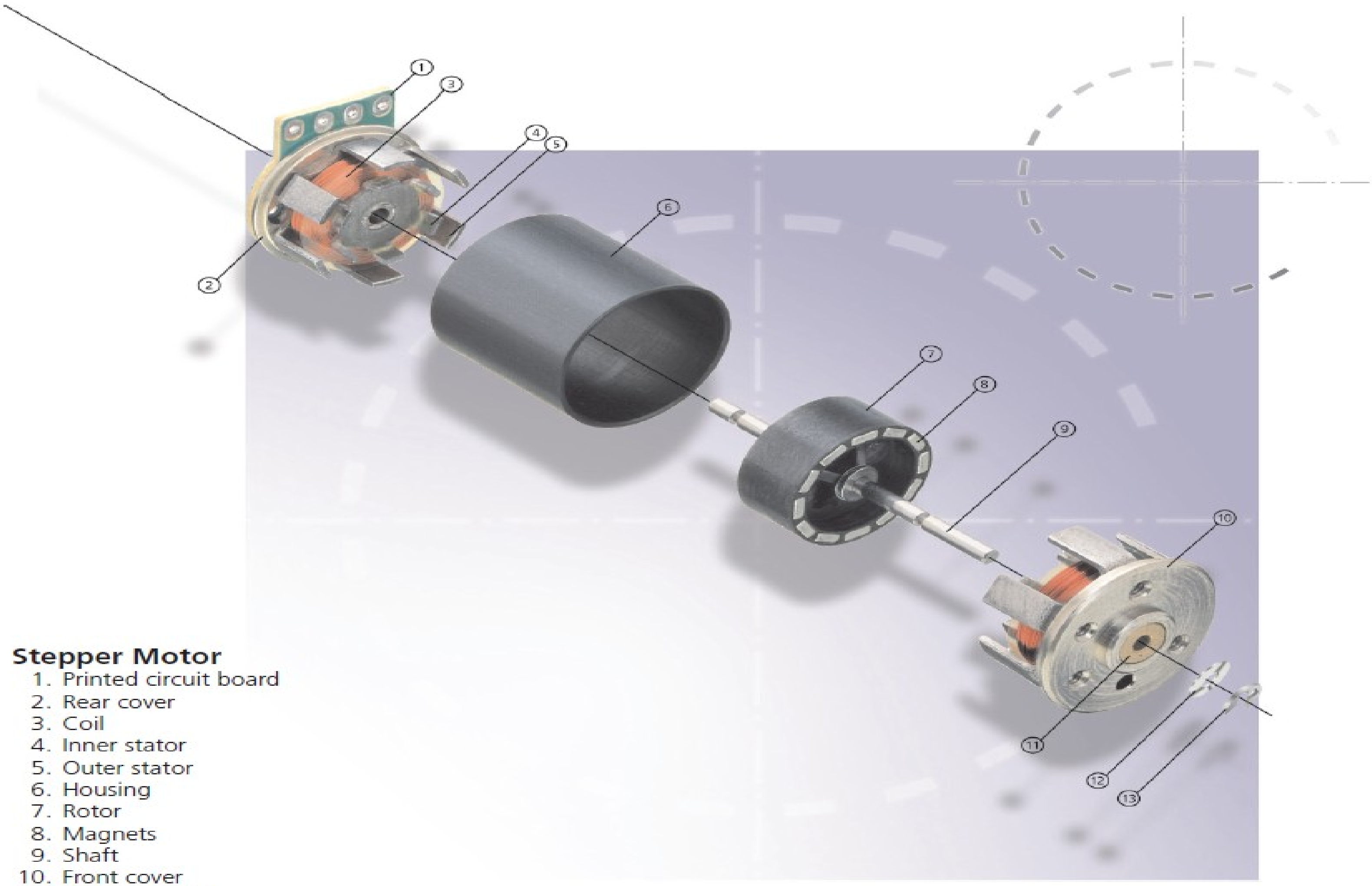
DC servos

- Speed range from very low to very high (over 50000 rpm)
- Power range from few W to few KW.
- Coulomb and viscous friction is a cause of concern
- Used in robot arms, X-Y plotters and recorders, gantry, CMMs, instruments
- Control by PWM or PRM

AC motors

- Typically brush free and suited to high power and high speed applications
- Frequency control is by field control and speed control requires complicated algorithms.
- Heavy and complicated construction
- High duty cycle, efficient and reliable.
- Used in trains, cranes, conveyors.

Stepper Motor



Stepper Motor

1. Printed circuit board
2. Rear cover
3. Coil
4. Inner stator
5. Outer stator
6. Housing
7. Rotor
8. Magnets
9. Shaft
10. Front cover
11. Sleeve bearing
12. Washer
13. Circlip

Stepper Motor

It is an incremental drive (digital) actuator and is driven in fixed angular steps.
A digital signal is used to drive the motor and every time it receives a digital pulse it rotates a specific number of degrees in rotation.
Each step of rotation is the response of the motor to an input pulse (or digital command).
Step-wise rotation of the rotor can be synchronized with pulses in a command-pulse train, assuming that no steps are missed, thereby making the motor respond faithfully to the pulse signal in an open-loop manner.
Stepper motors have emerged as cost-effective alternatives for DC servomotors in high-speed, motion-control applications (except the high torque-speed range) with the improvements in permanent magnets and the incorporation of solid-state circuitry and logic devices in their drive systems.
Today stepper motors can be found in computer peripherals, machine tools, medical equipment, automotive devices, and small business machines, to name a few applications.

Motor Types

Type	Features / Applications
Brush Type	Toys, battery powered tools and machines. Most common.
Brushless	High Efficiency, less electrical noise, less friction and hence less wear, requires electronic driver circuits.
Step Motor	Requires driver, easy to control rotor position. Most common.
Piezo (Ultrasonic)	New on the scene. No electrical coils. More torque along with axial load. Requires driver.
Linear	Same as brush type but moves load linearly

Stepper Motor Advantages

Position error is non cumulative. A high accuracy of motion is possible, even under open-loop control.
Large savings in sensor (measurement system) and controller costs are possible when the open-loop mode is used.
Because of the incremental nature of command and motion, stepper motors are easily adaptable to digital control applications.
No serious stability problems exist, even under open-loop control.
Torque capacity and power requirements can be optimized and the response can be controlled by electronic switching.
Brushless construction has obvious advantages.

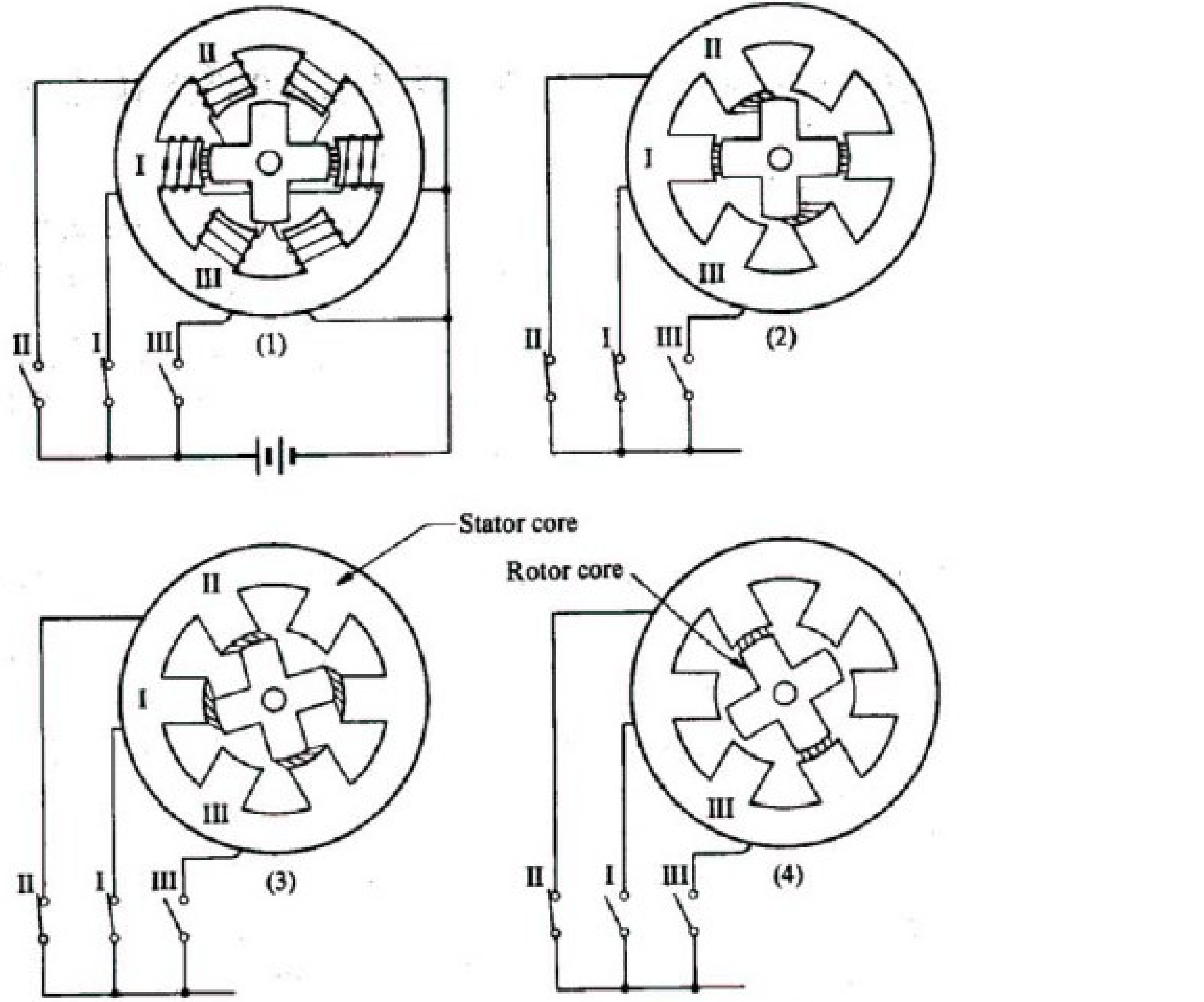
Stepper Motor Limitations

They have low torque capacity (typically less than 2,000 oz-in) compared to DC motors.

They have limited speed (limited by torque capacity and by pulse-missing problems due to faulty switching systems and drive circuits).

They have high vibration levels due to stepwise motion.

Large errors and oscillations can result when a pulse is missed under open-loop control.


II
I
III
(1)
II
I
III
(2)
Stator core
Rotor core
II
I
III
(3)
II
I
III
(4)

Stepper Motor Operation

Schematic belongs to a single-stack variable-reluctance motor. The stator core is the outer structure and has six poles or teeth. The inner device is called the rotor and has four poles. Both the stator and rotor are made of soft steel. The stator has three sets of windings as shown in the figure. Each set has two coils connected in series. A set of windings is called a “phase”. The motor above, using this designation, is a three-phase motor. Current is supplied from the DC power source to the windings via the switches I, II, and, III.
Starting with state (1) in the upper left diagram, note that in state (1), the winding of Phase I is supplied with current through switch I. This is called in technical terms, “phase I is excited”. Arrows on the coil windings indicate the magnetic flux, which occurs in the air-gap due to the excitation. In state I, the two stator poles on phase I being excited are in alignment with two of the four rotor teeth. This is an equilibrium state.

Stepper Motor Operation

Next, switch II is closed to excite phase II in addition to phase I. Magnetic flux is built up at the stator poles of phase II in the manner shown in state (2), the upper right diagram. A counter-clockwise torque is created due to the “tension” in the inclined magnetic flux lines. The rotor will begin to move and achieve state (3), the lower left diagram. In state (3) the rotor has moved 15°.

When switch I is opened to de-energize phase I, the rotor will travel another 15° and reach state (4). The angular position of the rotor can thus be controlled in units of the step angle by a switching process. If the switching is carried out in sequence, the rotor will rotate with a stepped motion; the switching process can also control the average speed.

Stepper Motor Operation

- Step Angle is the angle in degrees through which the rotor will turn per step.
  - Step Angle = 360 deg / S
  - S = number of phases * number of rotor teeth
- Step Sequencing: There are three modes of operation of a stepper motor. The mode of operation are determined by the step sequence.
- Wave Stepping: Low power consumption, less torque than full, less stable at high speeds.
- Full Stepping: Lowest resolution but highest torque.
- Half Stepping: Most torque, most stable at higher speeds and the highest resolution.

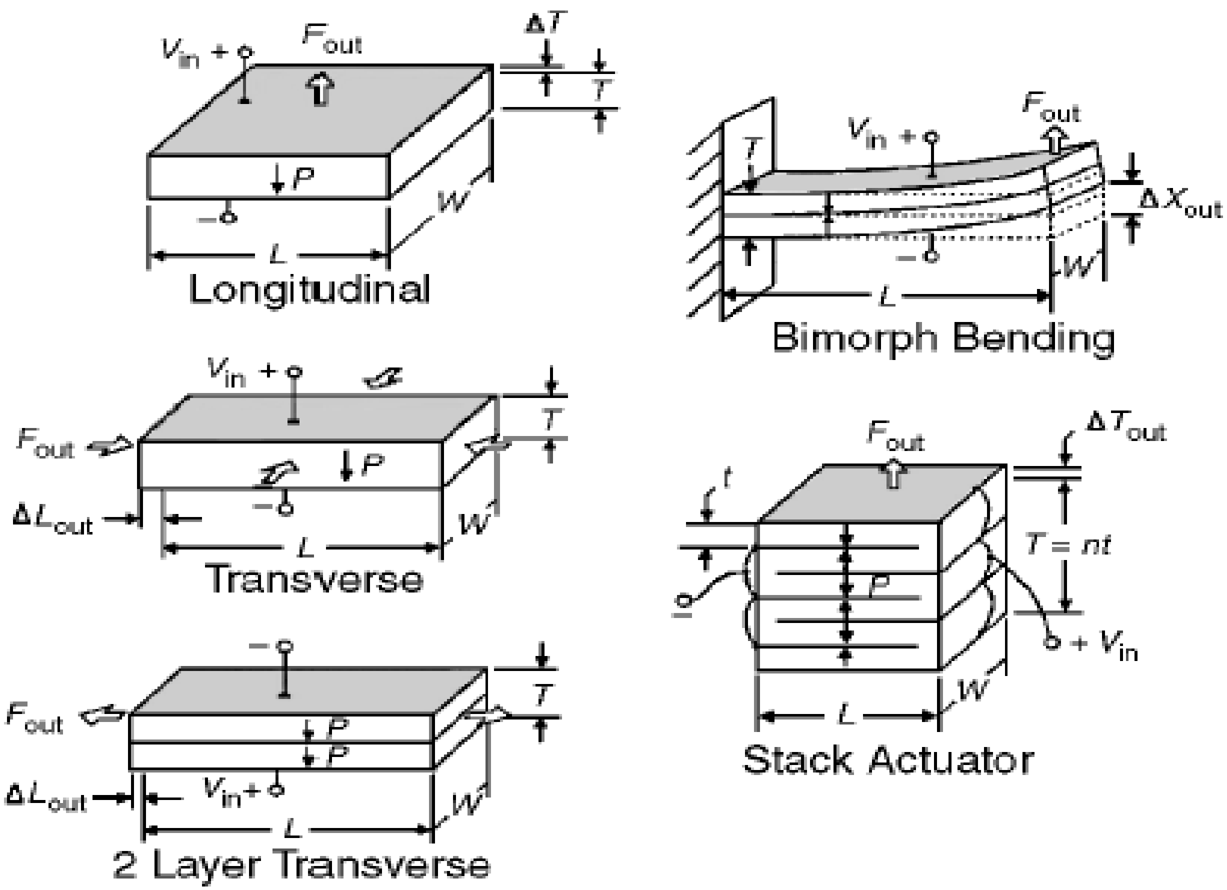
DC Motors vs Stepper Motors

Stepper motors are operated open loop, while most DC motors are operated closed loop.
Stepper motors are easily controlled with microprocessors, however logic and drive electronics are more complex.
DC motors have a continuous displacement and can be accurately positioned, whereas stepper motor motion is incremental and its resolution is limited to the step size.
Stepper motors can slip if overloaded and the error can go undetected. (A few stepper motors use closed-loop control.)
Feedback control with DC motors gives a much faster response time compared to stepper motors.

Piezoelectric Actuators

- Certain crystals produce electric voltage when deformed or deform when voltage is applied.
- A piezoelectric material produces asymmetric displacement in the crystal structure and in the charge centre of the of the affected ions. This causes charge separation and the voltage produce which is proportional to strain can be measured. This is the direct piezoelectric effect.
- The material will deform when voltage is applied. Reciprocal PE effect is used to produce mechanical actuation

Piezoelectric actuation methods



Piezoelectric Actuators

- Types of piezoelectric materials
  - Sintered Ceramics – Lead-zirconate-titanate. Larger force output and used mainly as actuators. Must be artificially polarised by strong electric current.
  - Polymers polyvinylidence fluoride PVFD. Larger deformation and used mainly as sensors.
  - Natural – quartz Rochelle salt
  - Synthetic crystals – lithium sulphate,ammonium dihydrogen phosphate

Piezoelectric motors

- Converts high frequency oscillations into mechanical motion
- Piezomotors have large torque, excellent control, high resolution, excellent controllability, small time constant, compactness, high efficiency, silent operation
- Classified on basis of oscillation conversion into continuous motion viz. Oblique impact and travelling wave motion type.

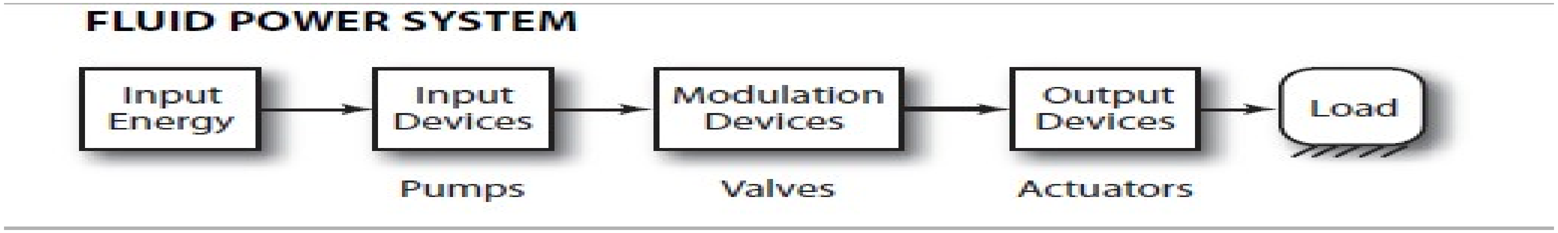
Areas of concern for Electromechanical Actuators

- High operating voltage, creep, hysteresis and fatigue
- Thermal runaway: As temperature increases conversion efficiency drops and more and more energy is dumped as heat which further reduces efficiency. This is called thermal runaway

Fluid Actuators

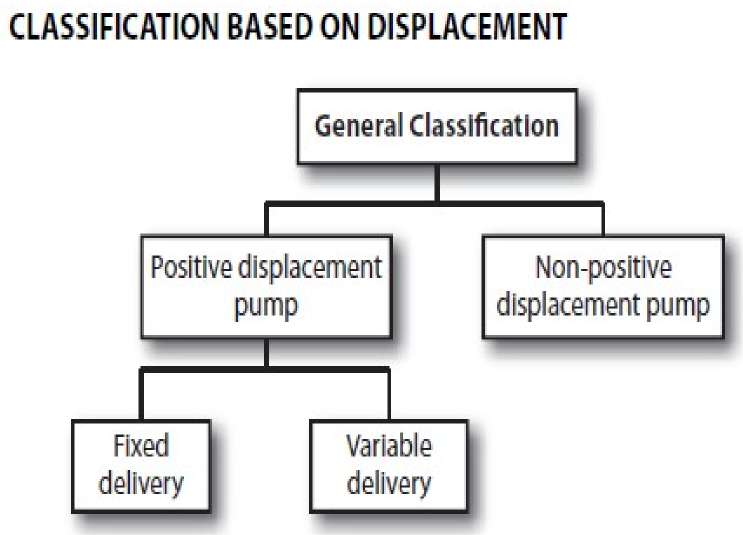
- Fluid servo systems are those which permit the control of one of the two property's which define fluid flow; pressure and flow rate.
- Pressure control – To effect force or torque control
- Flow control – For position, speed and acceleration control.

Elements of Fluid Power System



Transmitting fluid power requires a pump to convert the mechanical energy into fluid energy.
Proper devices are needed for the modulation of fluid actuators.
The primary source of input energy is quite often an electric motor, an internal combustion engine, or another type of mechanical device that can supply force and motion to operate the pumps.
The pump supplies hydraulic fluid or pneumatic pressure to the system. In other words, fluid power can be defined as the power transmitted and controlled through the use of a pressurized fluid.

Fluid Power Energy Input Devices



The input devices, such as pumps, are the primary source of fluid power energy creation.

The hydraulic pumps are used as devices that convert mechanical force and motion into actuating power using fluid power circuits.

Hydraulic pumps create flow of the fluid under consideration and develop pressure. Pressure is the direct result of resistance to flow encountered by the fluid.
The pressure can be varied by providing a different load to the system or by pressure regulating devices.

Positive Displacement Pumps

Positive-Displacement Pumps A positive-displacement pump has a small clearance between the stationary and rotating parts.

The positive-displacement pump is able to push a definite volume of fluid for each cycle of pump operation at any resistance encountered.

Because of its simplicity of use, positive-displacement-type fluid pumps are increasingly used in the fluid power industry.

The further subdivision of positive-displacement pump is as (i) fixed-delivery and (ii) variable-delivery types.

Positive Displacement Pumps

The fluid delivery of a positive-displacement pump depends on the working relationships of internal elements.

Volumetric output of the fluid remains constant for a given speed of the pump.

Only by varying the speed of the pump can the output of the pump be changed.

However, the fluid delivery in a variable pump can be changed by altering the physical relationship of the pump elements, keeping the speed at a constant level.

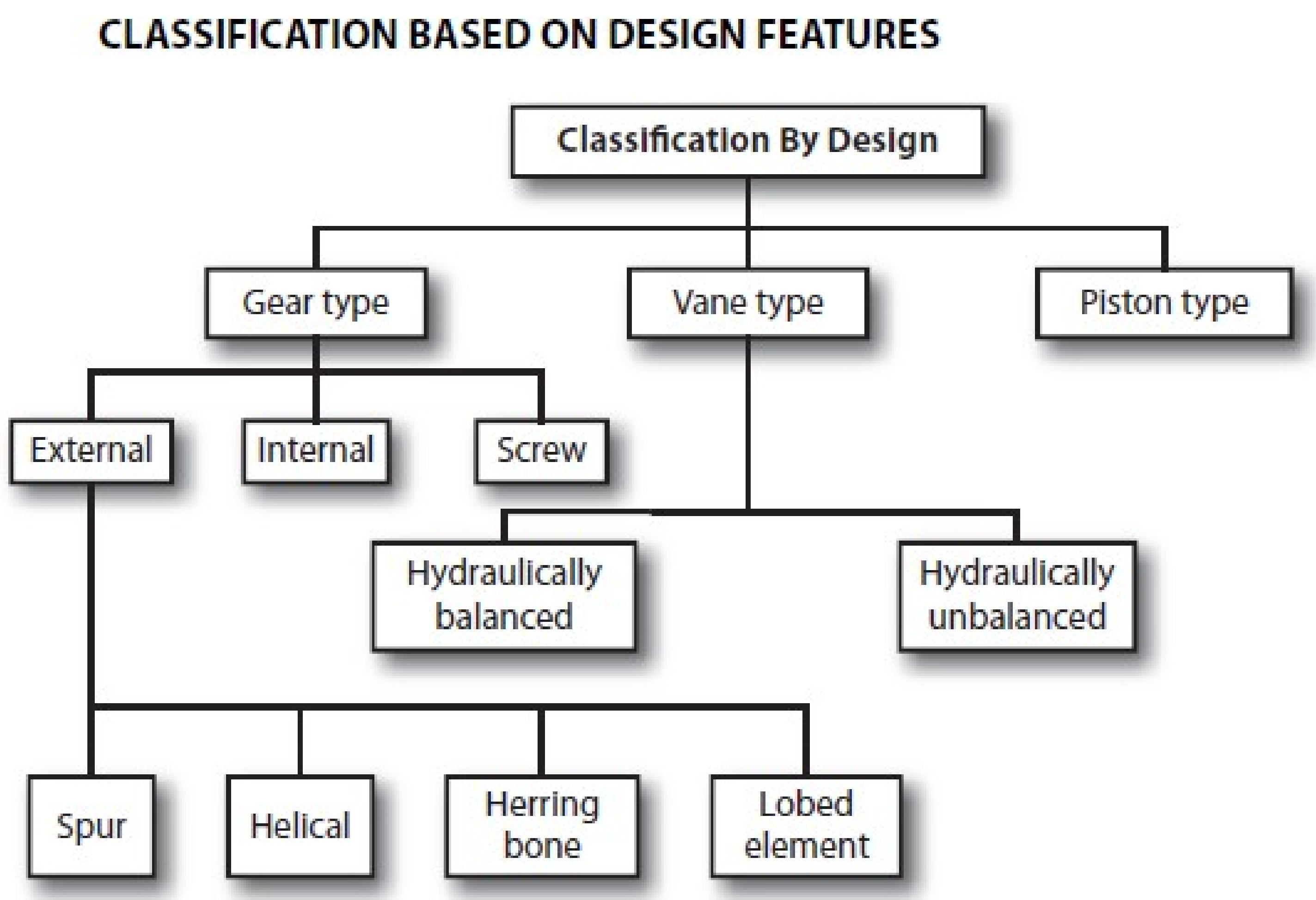
Non Positive Displacement Pumps

Non-Positive-Displacement Pumps A non-positive-displacement pump has a large clearance between the rotating and stationary parts.

The total volume of the fluid displaced from the pump depends on its speed and resistance faced at the discharge side of the pump unit.

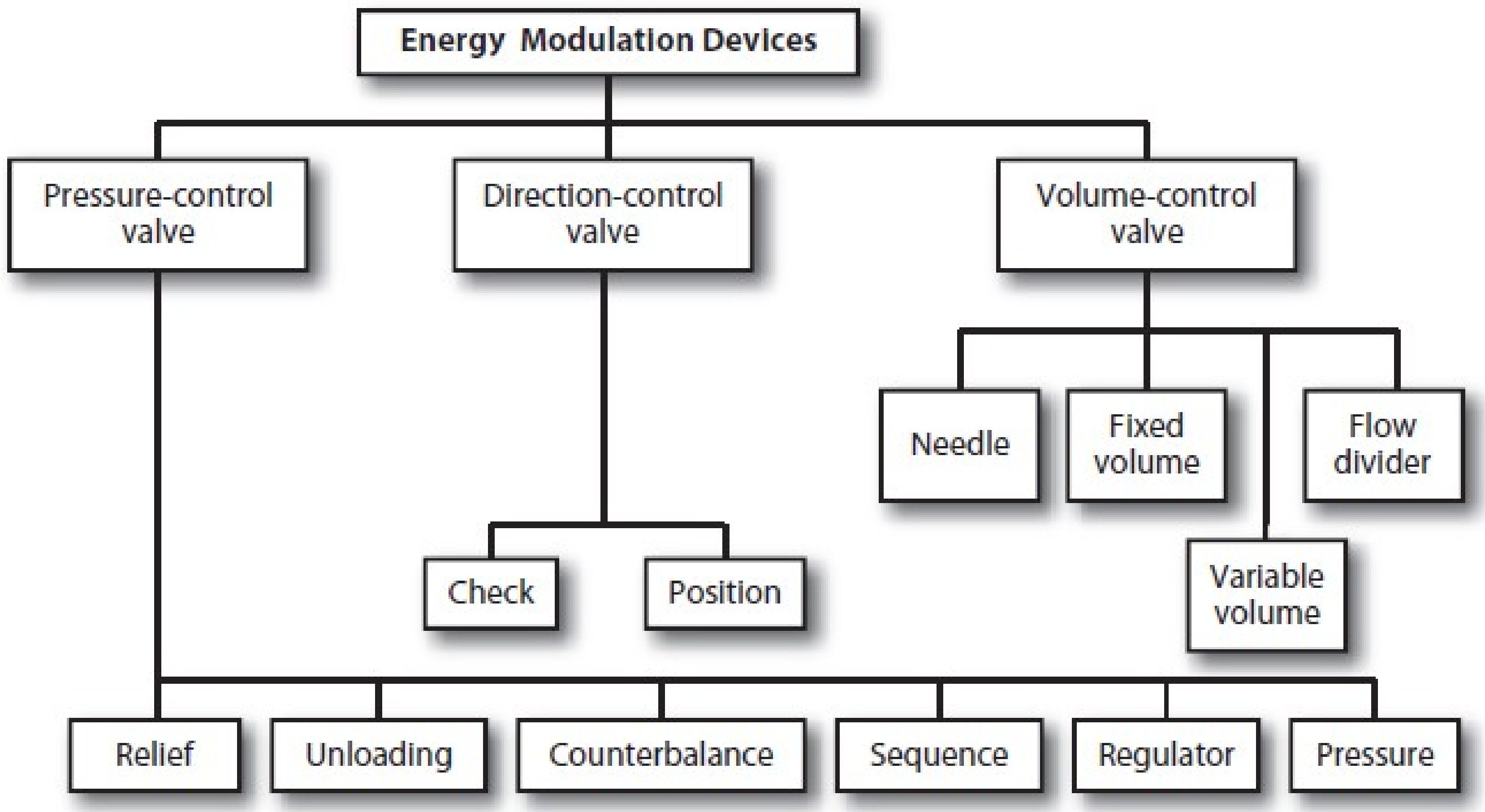
In applications which deal with a low-pressure and high-volume flow situation, non-positive-displacement pumps are used.

Pump Classification by Design



Modulation Devices

FIGURE 4-21 ENERGY MODULATION DEVICES



Energy Output Devices

Fluid power energy-output devices provide either linear or rotary motion through the use of actuators, called cylinders, and fluid motors.

Fluid actuators use hydraulic power of the order of 35 MPa. This gives the fluid actuators a capability to provide higher torques and forces at a very high power level. A fluid cylinder is a device that converts fluid power into linear mechanical force—into motion. It consists of a movable element such as a piston and piston rod, operating within a cylindrical bore.

A fluid motor is a device that converts fluid power into rotary mechanical force and motion.
Fluid motors and fluid pumps are similar in many respects, but the fluid motor works in a manner just opposite to the way in which pumps work. Fluid motors use the fluid delivered by a pump to provide rotating force and motion.

Fluid Motors

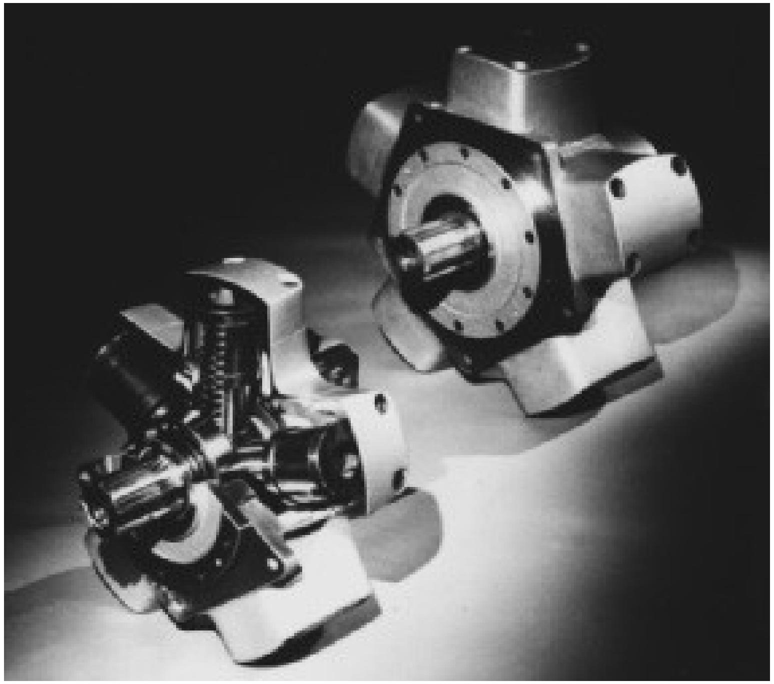
A fluid motor is capable of converting fluid power into rotary mechanical power. A properly controlled motor can produce an output which has reversible and variable speed characteristics.

Rotary fluid power motors provide a higher horsepower-to-weight ratio than do other sources of power. The rotary fluid motors have good variable speed and torque characteristics.

There are two general classes of fluid motors:

- Fixed-displacement motors
- Variable-displacement motors – Gear motor, Vane motor, Piston Motor

Radial Piston Motor



Control of Fluid Power Systems

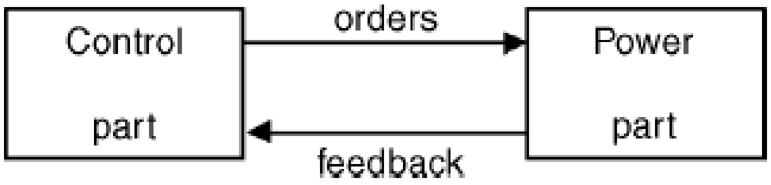
- Manual Control
- Mechanical Control
- Fluid Control
- Electrical Control – All kinds of switches, timers, relays used to operate solenoids that control position valves.
- Mechatronic Control

Why prefer fluid power?

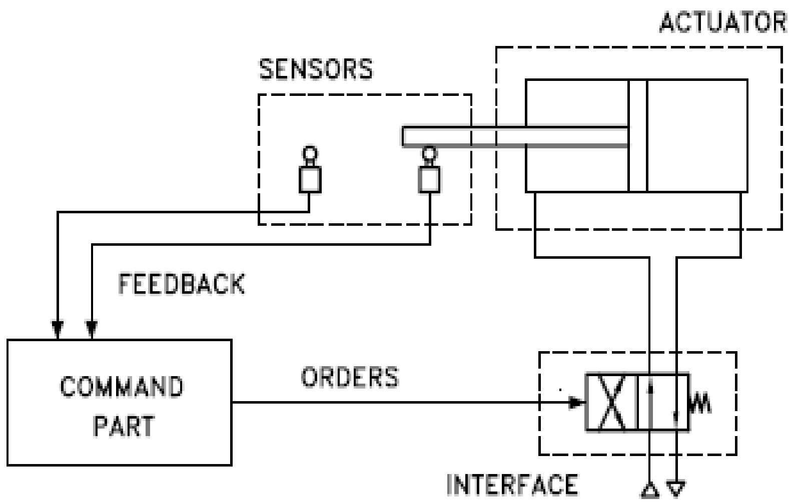
- Continuous control of force or speed is better with fluid device because of the following points.
- Maintain system under load without excessive use of control devices.
- Linear movements at high speed over longer lengths
- Higher bandwidth

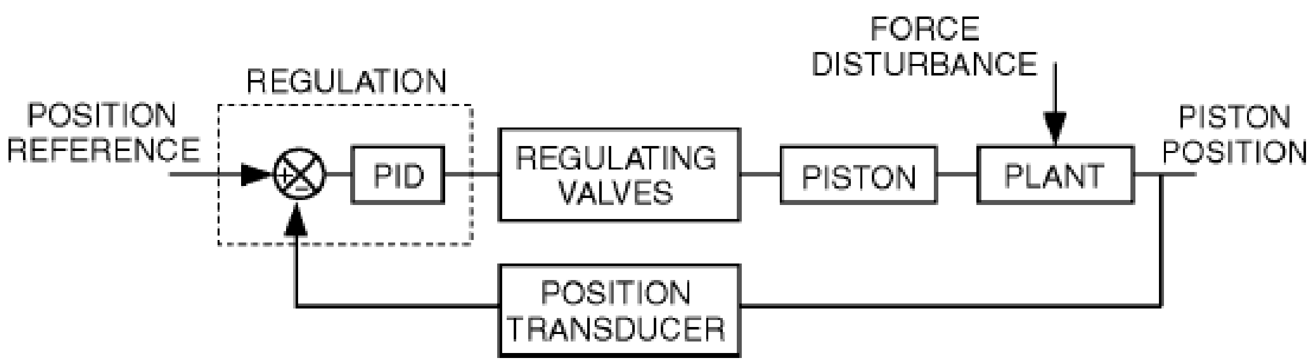
Typical actuation system

- Power part – Consists of all devices that effect the action
- Control part – Process information, enable feedback, generate the operation cycle
- Interfaces – Send the orders to the power part, convert and amplify signals. Can be speed drives or distributor valves.



Typical FP actuation system





Hydraulic Actuators and Valves

- Hydraulic pressure acts on piston
- Can be single acting or double acting, double cylinder double rod
- Efficiency depends upon friction
- Valves are on/off type, proportional or servo
- Control – Manual (for on/off) electric over hydraulic, hydraulic over hydraulic.
- Used when large force, high power and rugged operating conditions.
- Applications : Ailerons actuation, rockets etc., automotive steering and brakes

Hydraulic actuation system components

- Pump – hydraulic power generator
- Actuator – convert hydraulic power to mechanical
- Fluid – transfer hydraulic power
- Valves – regulate power
- Pipe fittings - connections
- Sensors Display and control
- Filters

Pneumatic actuation system components

- Compressed air source - power source
- FRL unit
- Valve
- Actuator – convert pneumatic power to mechanical power
- Sensors display and control devices
- Piping and other instrumentation

Pneumatic actuators

- Used for low power density, low cost , quick installation, moderate accuracy
- Used in assembly line for moving parts, robot grippers, suction, clamping

Actuator Selection

The major factors in selecting an actuator for mechatronic applications are

- Precision
- Accuracy and resolution
- Power required for actuation
- Cost of the actuation device