EE Dept, IIT Bombay
Academic Year: 2024-2025, Semester II (Spring)

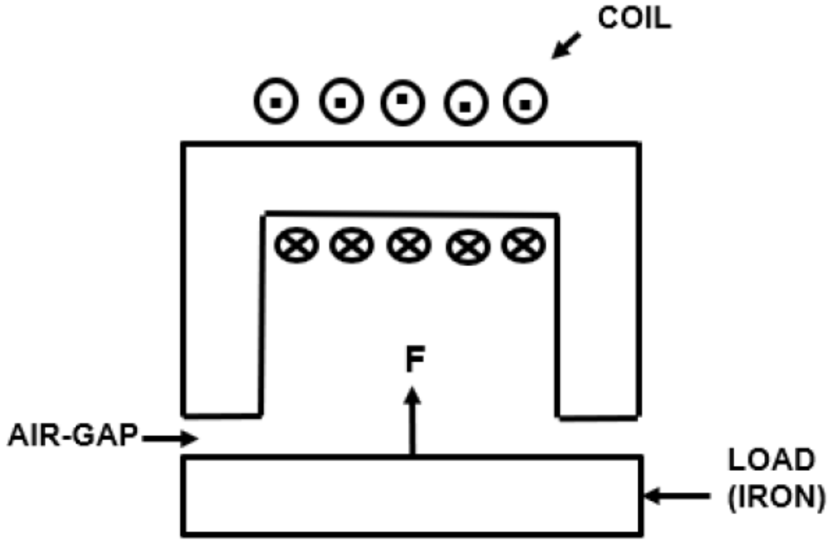
Course: MS101 Makerspace

EE Lecture 11
Electromechanical Components

Topics
1. Electromagnet
2. Electromagnetic Relay
3. Relay Control
4. Solenoid
5. DC Motor
6. Brushless DC Motor
7. DC Servomotor

1. Electromagnet

- It consists of a magnetic core (soft iron or steel) and an exciting coil. Current flow in the coil results in magnetic field distribution with corresponding N and S poles. The magnetic field direction is reversed by changing the current direction.
- A high flux density (B) can be obtained in the air gap, subject to the core saturation. Energy stored in the air gap is used to carry out various functions (lifting material, closing/ opening contacts, etc.).
- Its main applications involve pulling an iron piece as a load. The pulling action is not affected by the current direction does not affect the pulling action.



Tractive force across each air-gap: $f = \frac{(B)^2 A}{2\mu_0}$

B = flux density in the air gap (assumed as uniform).
A = cross-sectional area of pole-face.
Total force: $F = 2f$.
The total force should be able to hold the load weight: $F \geq mg$.

Electromagnet application example

Relocation of steel pipes

2. Electromagnetic Relay

It is a device for switching large voltages and currents using a relatively small current to control the excitation coil of an electromagnet. It is also known as electromechanical relay or EM relay.

Most Common EM Relays: **Attracted Armature type.**

It consists of

a) a moving part (armature) capable of making electrical connection with two contacts,
b) an electromagnet with an excitation coil wound on a magnetic core, and
c) a restraining spring.

Force on the armature: $\boldsymbol{F = KI_{rms}^2 - C}$
I = current through the excitation coil,
K = proportionality constant,
C = force offered by the restraining spring.

Relay operation depends on the coil ampere-turns, the air-gap between the armature and the core, and the restraining force of the spring.

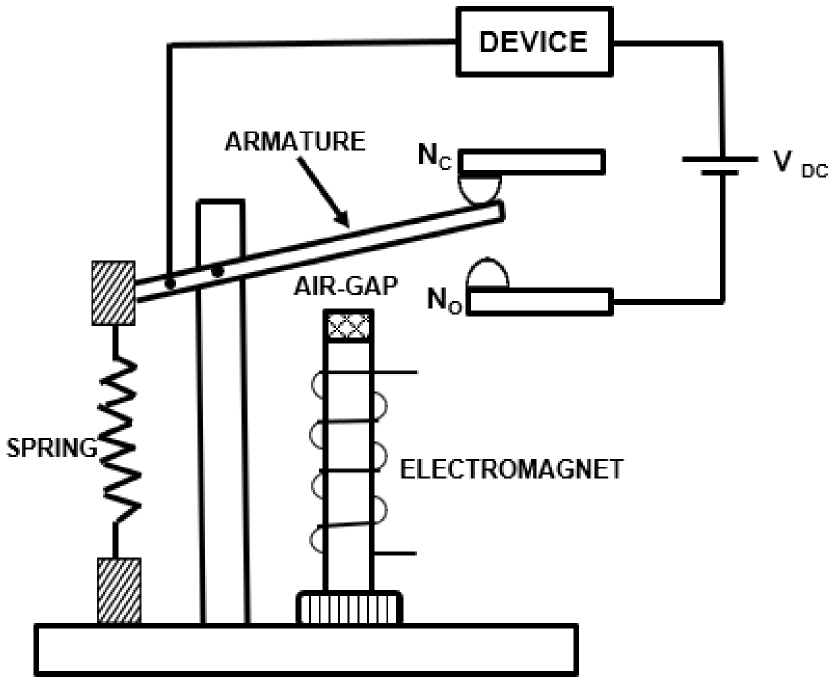
Attracted Armature Type Relay Operation

- A coil wound over a ferromagnetic material forms an electromagnet.
- Armature is the moving part of the magnetic circuit. It controls contacts and is restrained by a spring.

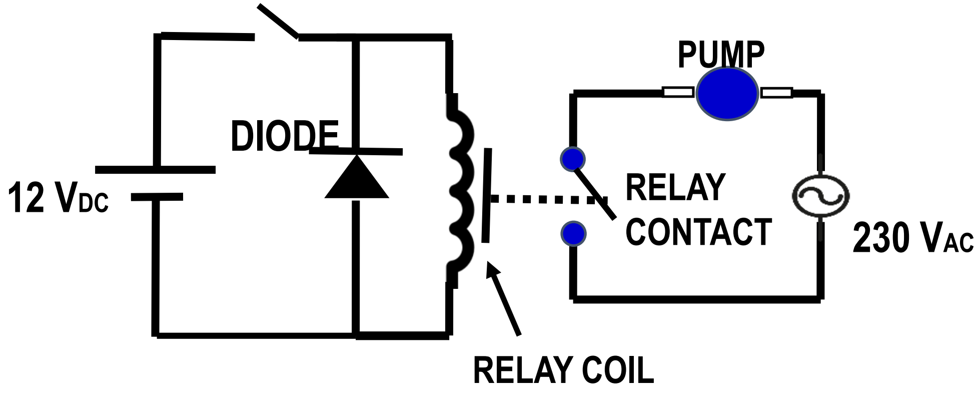
NC contact: Normally Closed in unexcited mode.

NO Contact: Normally Open in unexcited mode.

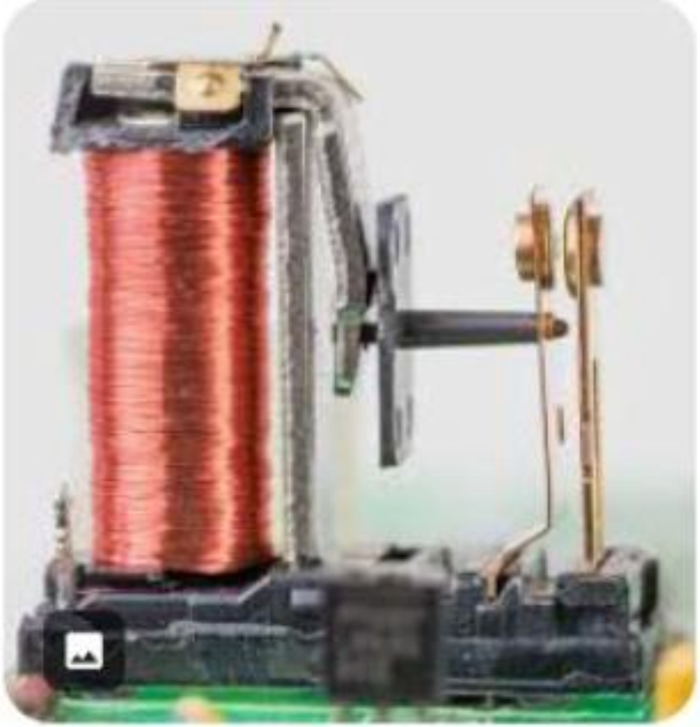
- When the coil is excited, the armature is attracted towards the NO contact. When the excitation current is turned off, the restraining force of the spring restores the armature to the NC contact.
- The armature movement between the two contacts makes and breaks the circuit with supply Vcc and DEVICE.
- The excitation circuit controlling the relay coil current is electrically isolated from the load circuit connected to the relay contacts.



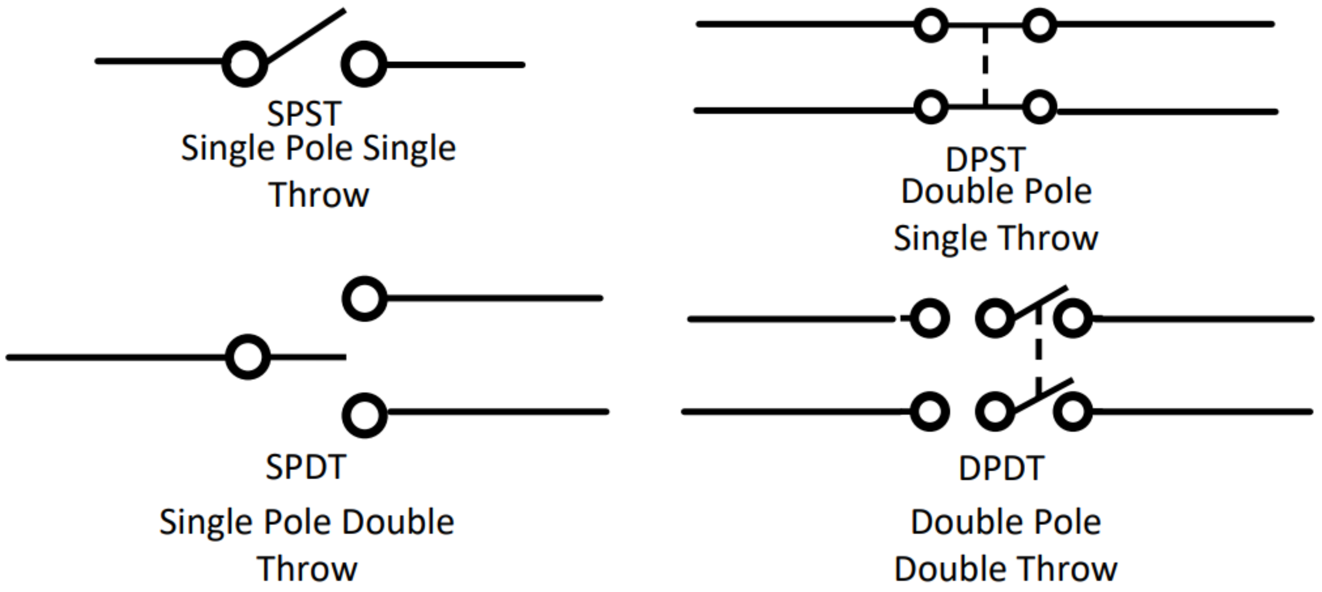
Water pump ON-OFF control



Relay Examples



Relay Nomenclature



Application examples

SPST: On/off control of a load circuit by switching in one wire (e.g., AC mains phase wire).

DPST: On/off control of a load circuit by simultaneous switching in both wires (e.g., AC mains phase & neutral).

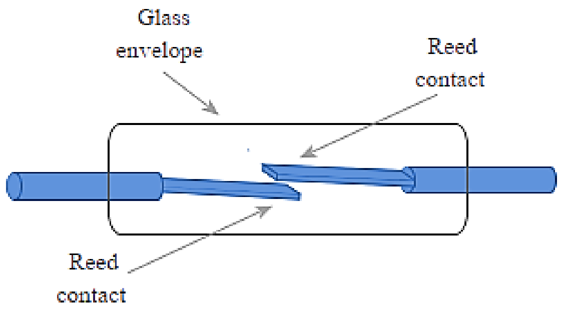
SPDT & DPDT: Complementary on/off control of two load circuits.

Reed Relay

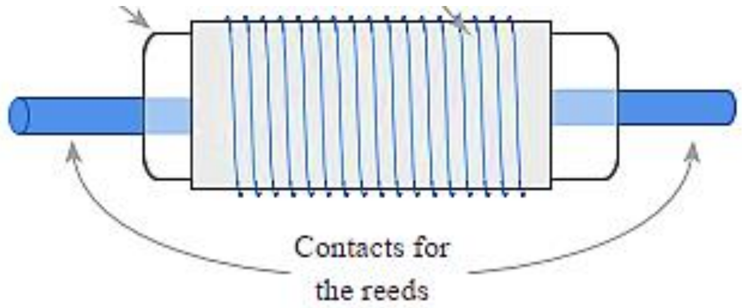
In this type of EM relay, the switch contacts are made of a ferromagnetic material, and the electromagnet acts directly on them without requiring an armature and spring. The contacts are sealed in a glass tube and protected from corrosion. The coil is placed around the tube.

- **There may be multiple switches in the same tube.**
- **They can switch fast because they have small and lightweight moving parts.**
- **They require low operating power and have low contact capacitance.**
- **They are available in small packages.**
- **They have longer life, but lower current & voltage handling capacity than the armature-based relays.**

Reed switch inside the glass tube (reed: thin, wide, & flexible part, resembling the reed of a musical instrument)



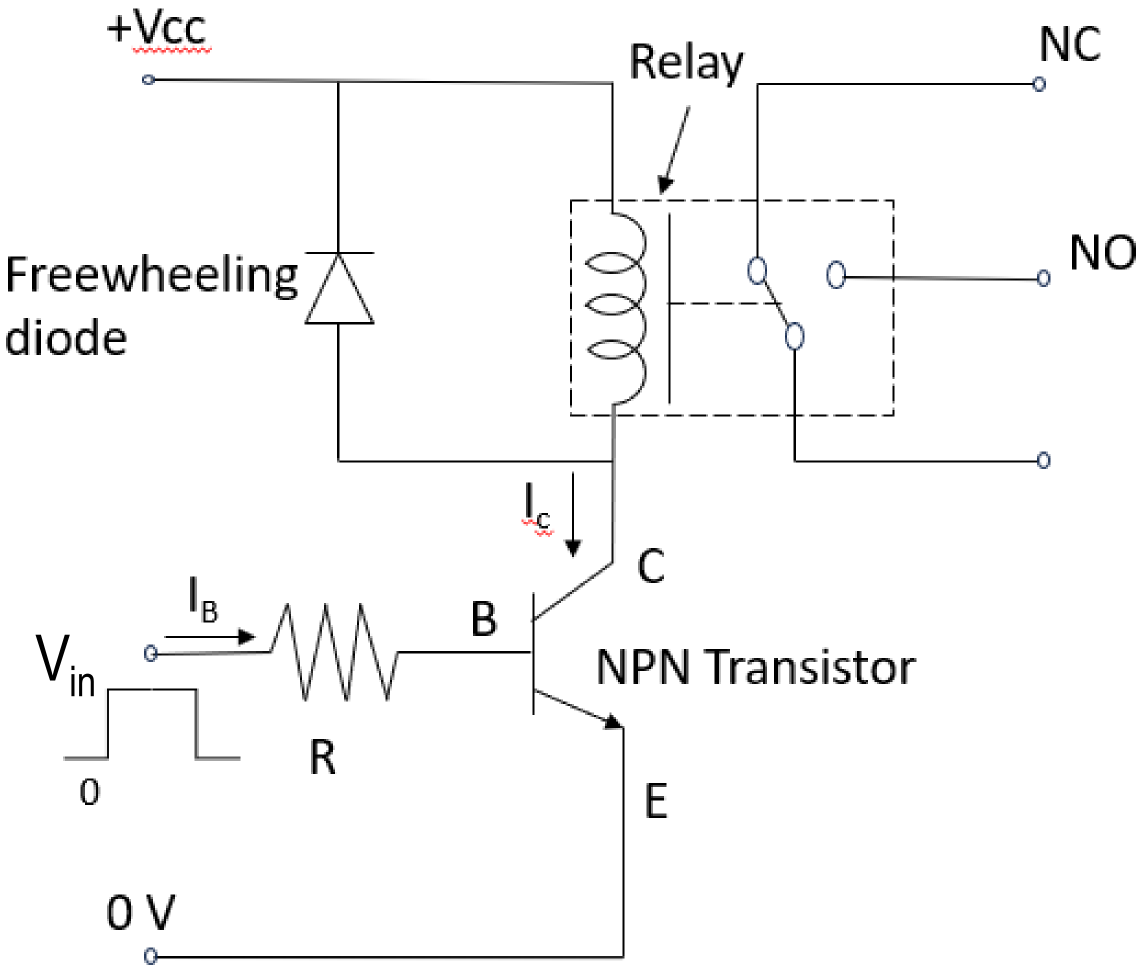
Reed relay (coil outside & reed contact inside the glass tube)



Packaged reed relays

3. Relay Control

NPN transistor circuit to control the relay coil connected to the positive supply end (Vcc)



On-state: $V_{BESat} \approx 0.8$ V. $V_{CESat} \approx 0.2$ V.

Collector current: $I_C = (V_{cc} - V_{CESat}) / R_{coil}$

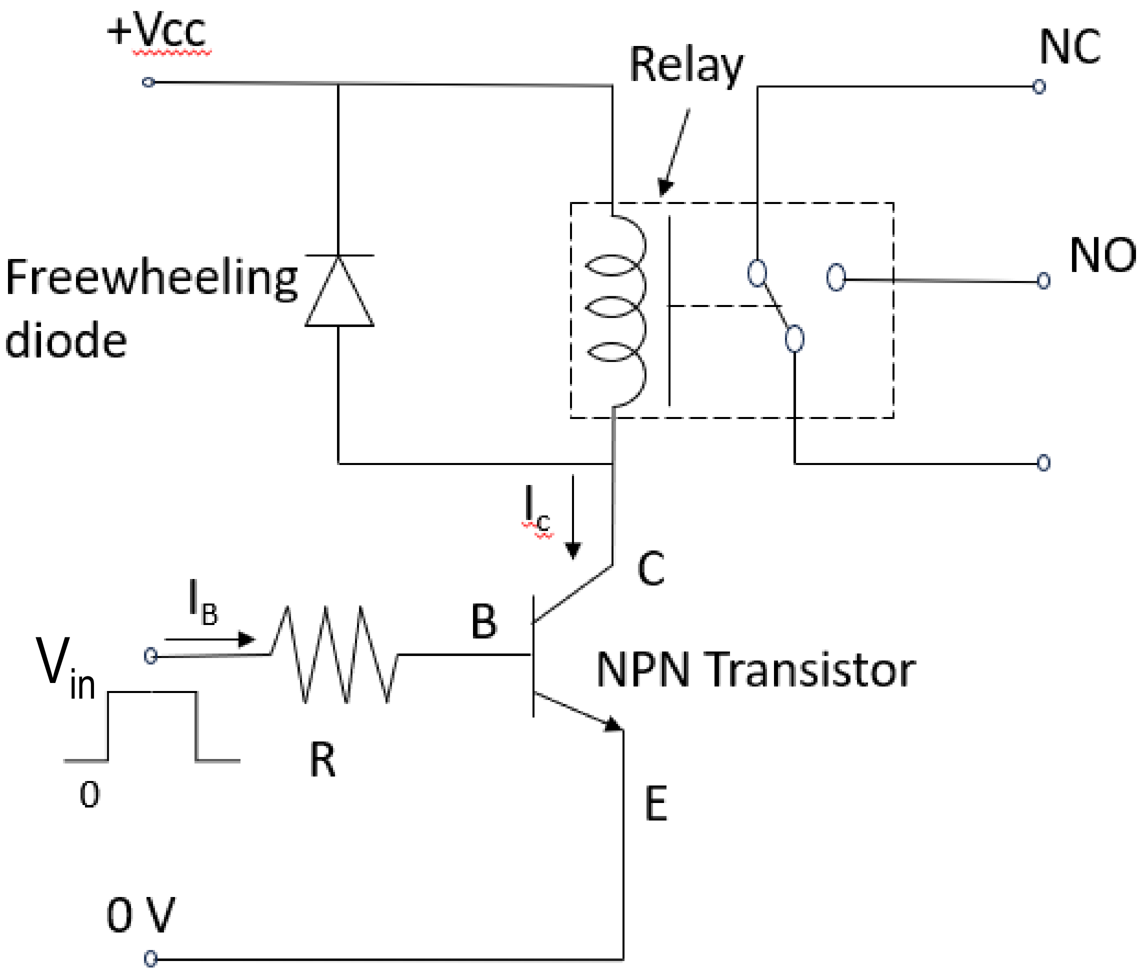
Current gain: $\beta = I_C / I_B$.

For transistor in saturation mode, $I_B > I_C / \beta_{min}$.

Vin & R should be such that $I_B = (V_{in} - V_{BESat}) / R > I_C / \beta_{min}$.

Off-state: $V_{in} < V_\gamma$, $V_\gamma = 0.5$ V. $I_B \approx 0$. $I_C \approx 0$.

- Voltage developed across an inductor: $V = L\, di/dt$
- When the transistor turns off, a sudden reduction in the coil current gives rise to a large reverse voltage at the transistor's collector terminal.
- The freewheeling diode avoids damage to the transistor. It limits the collector voltage to $V_{cc}+V_D$. The coil current exponentially decays to zero (with time constant L_{coil}/R_{coil}).



Example

R_{coil} = 225 Ω.

V_{CEsat} = 0.2 V. V_{BEsat} = 0.8 V. β_{min} = 35.

V_{cc}= 12 V. V_{in}(off) = 0 V. V_{in}(on) = 5 V.

Find *R* and the on-state coil current.

On-state

$$I_C = (V_{cc} - V_{CEsat})/R_{coil}$$

$=$(12− 0.2) / 225 $=$ 52.44 mA

$I_B > I_C/\beta_{min}$ = 52.44 / 35 = 1.50 mA

V_{in}= 5 V.

I_B= (V_{in}—V_{BESat}) / *R* = (5-0.8) / *R* = 4.2 / *R* >1.50 mA

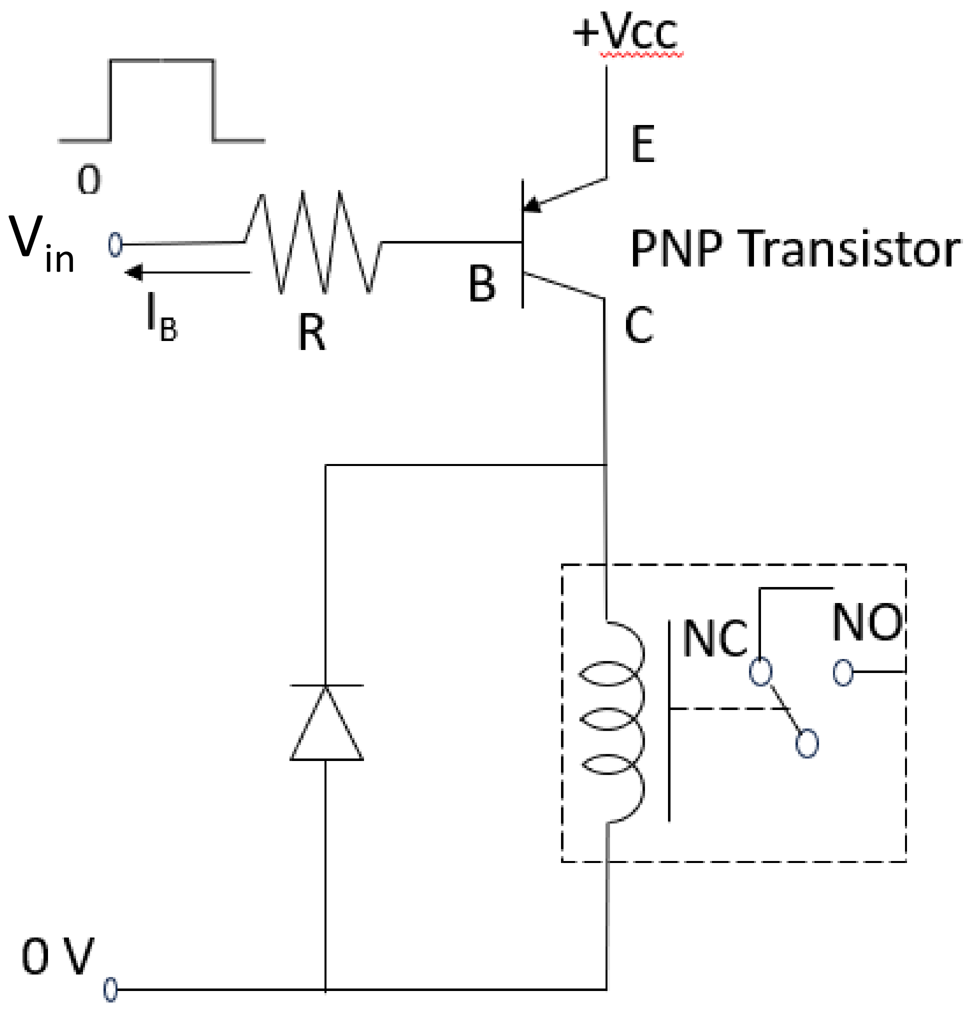
⇒*R*< 4.2/1.50 kΩ = 2.8 kΩ.

Therefore we can use *R* = 2.7 kΩ.

PNP transistor circuit to control the relay coil connected to the negative supply end (GND)

The relay coil in both circuits is on the collector side.

- **PNP transistor circuit: one terminal of the relay is connected to GND.**
- **NPN transistor circuit: one terminal of the relay is connected to V_{cc}.**

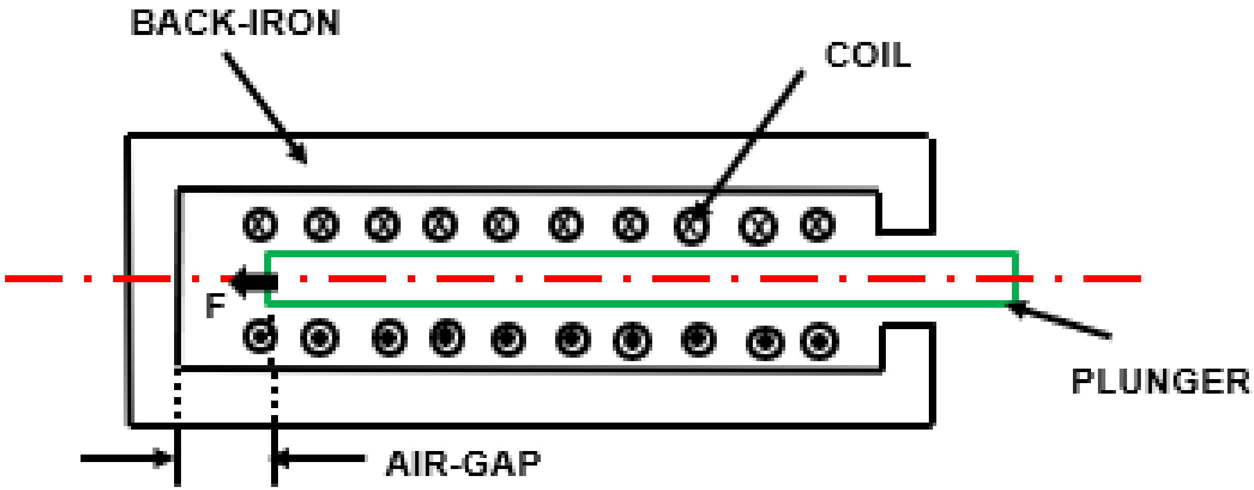


4. Solenoid

- It is an electromechanical actuator that uses electrical energy to cause mechanical movement.
- It is normally used to
  a) push or pull a plunger (linear motion),
  b) realize rotatory motion (over an angle),
  c) open or close a valve.

Typical Construction of a Linear Solenoid

- A movable plunger or armature is placed concentrically inside a coil.
- Back-iron provides a low-reluctance magnetic path for flux.



- Coil current creates a magnetic field.
- Coil is driven like a relay coil.

Force: $F = \frac{(B)^2 A}{2\mu_0}$ $\qquad B \cong \mu_0 \frac{NI}{l}$

N = number of turns. *I* = coil current. l = airgap length. *A* = plunger cross-sectional area. *B* = air-gap flux density.

Solenoid Examples

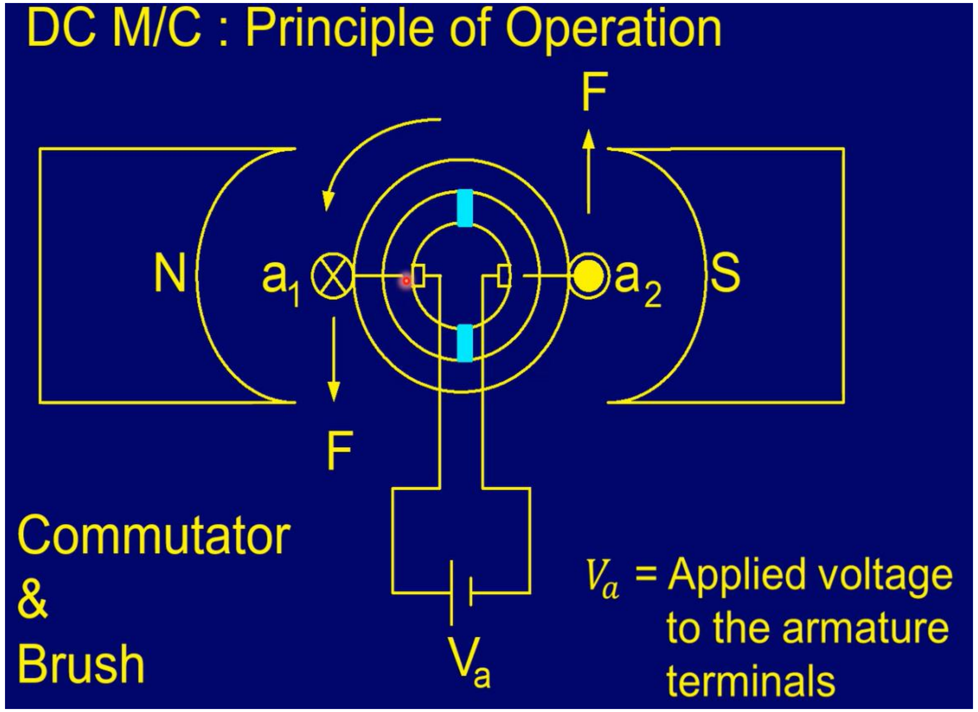
Linear motion solenoid with restoring spring

Bidirectional rotary solenoid

Solenoid-controlled fluid valves

5. DC Motor

It is a DC-powered electromechanical device using interaction between the magnetic fields of a stator and a rotor (armature) for rotary motion of a load connected to its shaft.



Conventional Brushed DC Motor

- Stator field is produced by its coils (electromagnets). Rotor coils have their two sides (a1 and a2 in the figure) pole-pitch apart under N and S poles.
- Rotor conductors carrying current and placed in the stator field experience force as per Fleming's Left Hand Rule (index finger: stator field direction, middle finger: current direction, thumb: force direction).
- As the rotor moves and the two coil sides exchange their positions, the directions of their currents are reversed by a commutator-brush arrangement to produce unidirectional torque.

Reference:
https://docs.google.com/presentation/d/1s1Fsvb0INAqGS9AAog9YmkMy3jo-zmj6/edit?usp=sharing&ouid=111902402391197382365&rtpof=true&sd=true
To listen to the video, first download the shared PPT file, and then put it into slide show.

- As the rotor coil moves in the field of the stator, a back electromotive force (e.m.f.) E_b is induced in the rotor conductors, opposing the applied voltage V_a.

- $V_a = E_b + I_a R_a$

  I_a = armature current. R_a = armature resistance.

- $E_b = K_e \phi \omega$.

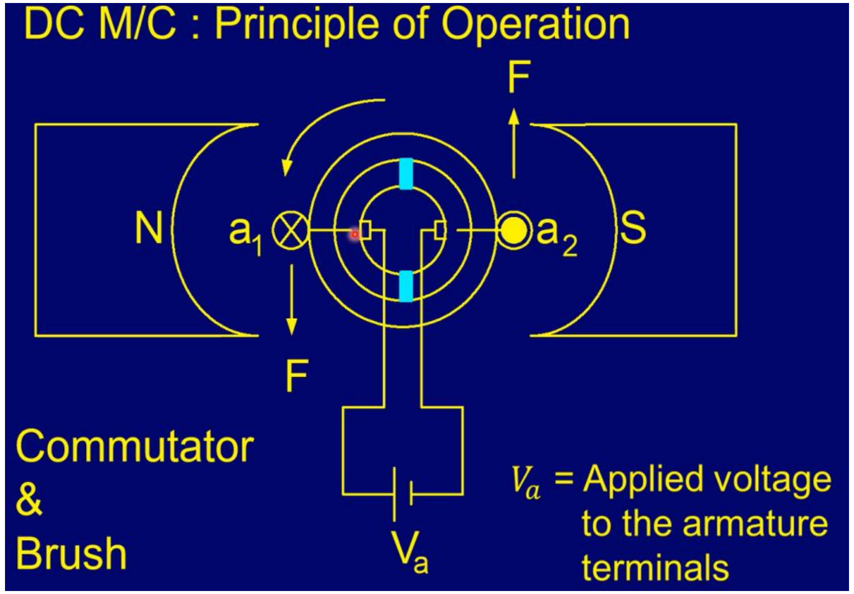
  Torque $T = K_e \phi I_a$

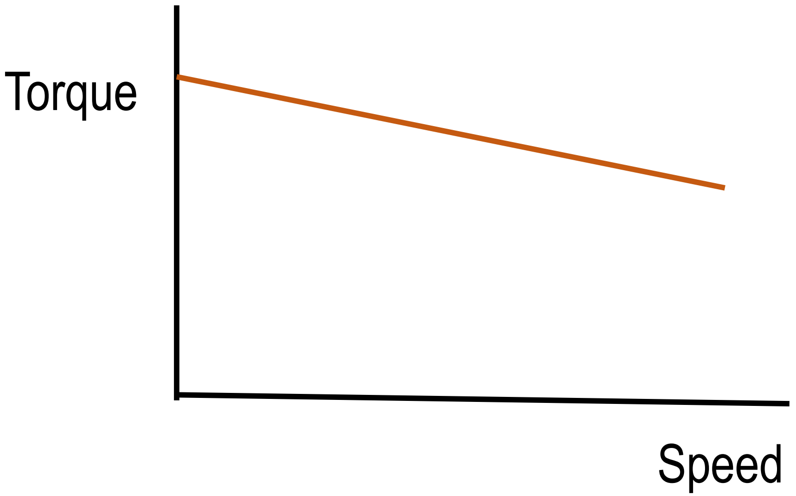
  K_e = machine constant. ϕ = flux. ω = and rotational speed.

  $\omega = V_a / (K_e \phi) - R_a T / (K_e \phi)^2$

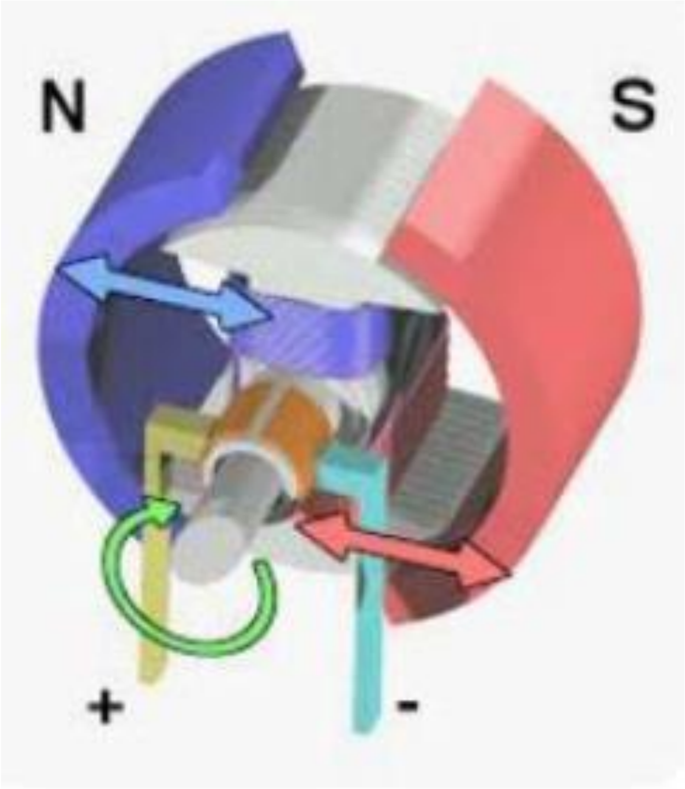
- For a given rotor coil voltage and stator field (stator coil current), speed decreases as the torque increases.

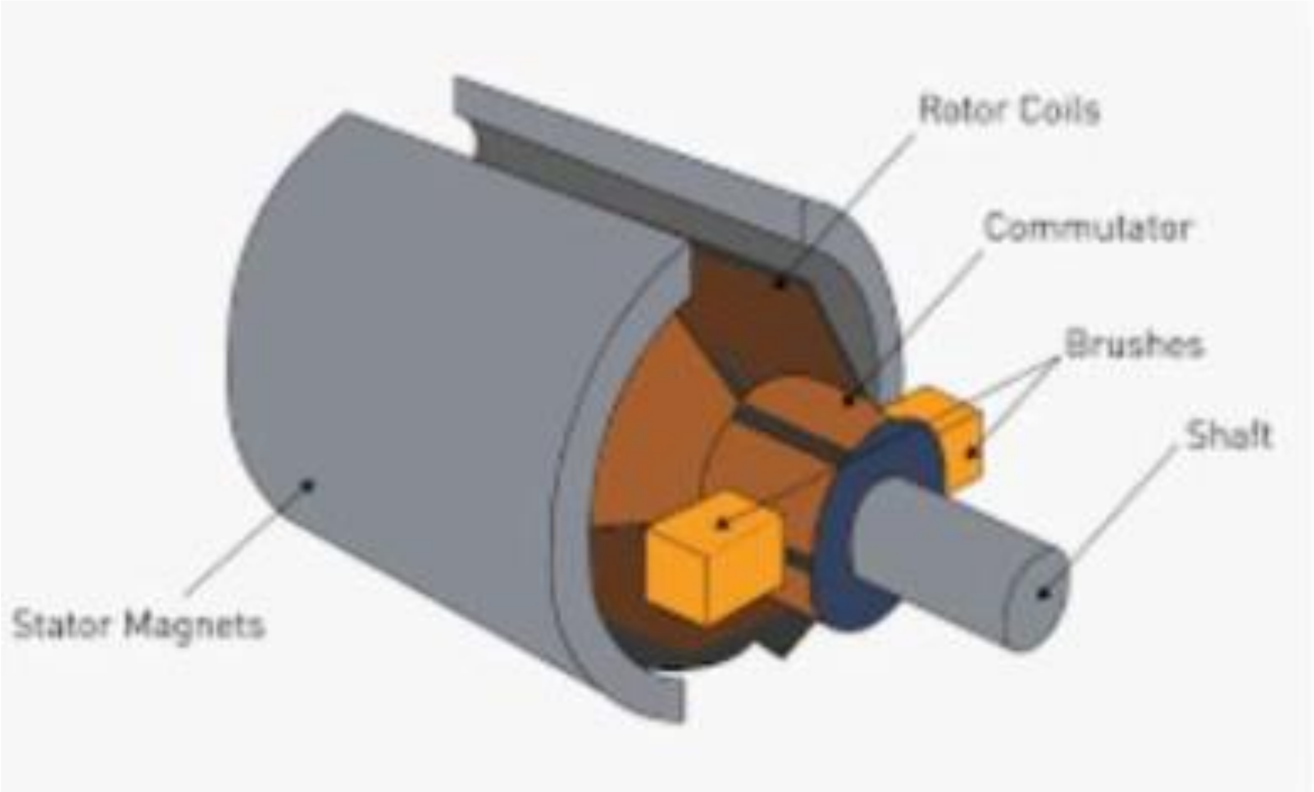
- For a given torque, speed can be increased by increasing the rotor coil voltage.





Brushed Permanent Magnet DC (PMDC) motor: internal parts





Brushed Permanent Magnet DC (PMDC) motor

The stator field is produced by permanent magnets. In these motors, only the rotor coil needs current.

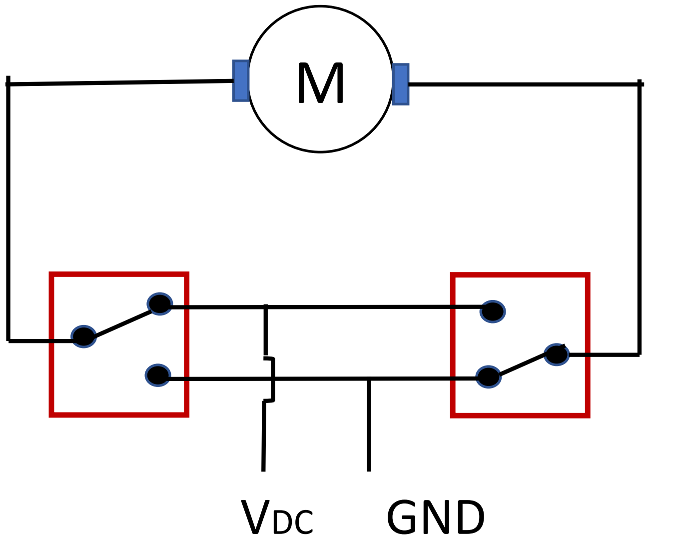
- The direction of currents flowing in the rotor coils forming electromagnets are changed appropriately through the commutator-brush arrangement to produce unidirectional torque in accordance with the principle that like poles of the stator and the rotor repel and their opposite poles attract each other.
- During the current direction reversal in the rotor coils, the currents may get reversed before becoming zero. The coils have inductance, and interruption of non-zero currents in them results in large voltages between the commutator segment and the brushes, causing sparking between them. It results in large spikes in the applied DC voltage.
- To mitigate the effect of voltage spikes on the connected electronic components in the circuit, a suitable capacitor is connected across the BO motor terminals (as in Experiment 4).
- The speed of a BO motor can be varied by changing the applied DC voltage. The rotation direction can be controlled by changing the polarity of the applied voltage. These controls can be carried out using two SPDT switches or four SPST switches (H bridge).

Battery-operated (BO) motors are geared PMDC motors, with the gears used for increasing the torque with a corresponding decrease in speed.

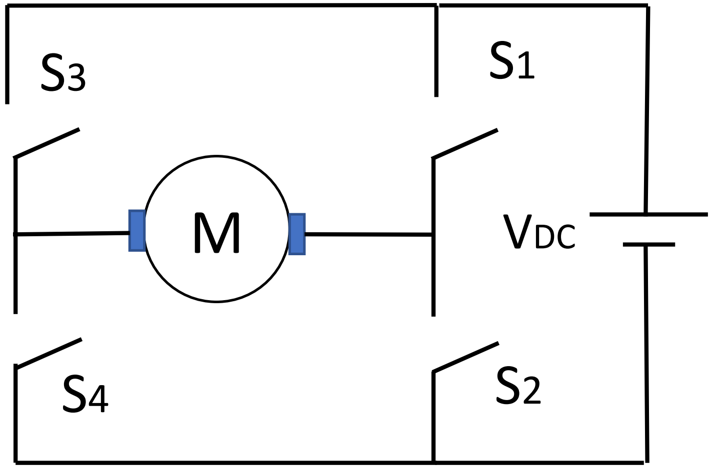
Reference: Write-up on BO motors.

DC (BO) Motor Direction Reversal

Direction Reversal Using 2 SPDT Switches



Direction Reversal Using H-bridge (4 SPST Switches)



The speed and direction can be controlled electronically using transistor switches connected as H-bridge and freewheeling diodes. These circuits are available as motor driver cards (e.g. L298). The speed is controlled by changing the average DC voltage by controlling the on/off duty cycle of the switches, known as pulse width modulation (PWM) control.

S1	S2	S3	S4	Action
0	0	0	0	Motor Coasts (unpowered)
0	0	1	1	Short Circuit (must be avoided)
0	1	0	1	Breaking
0	1	1	0	CW Movement
1	0	0	1	CCW Movement
1	0	1	0	Breaking
1	1	0	0	Short Circuit (must be avoided)
1	1	1	1	Short Circuit (must be avoided)

6. Brushless DC (BLDC) Motor

The rotor is of inner or outer type with permanent magnets and the stator has electromagnets with the coil currents commutated electronically.

- **Disadvantages of brushed motors**

- High maintenance and short lifespan because of wear and tear of brushes.

- Low efficiency on account of friction between brushes and commutator segments (energy loss and heat).

- **Brushless motors**

- Higher efficiency, lower maintenance, compactness, higher power-to-size ratio, and lower noise

- The stator houses a star or delta-connected three-phase coils (acting as electromagnets).

- Electronic speed controllers commutate currents in the stator coils producing unidirectional torque. The currents in the stator coils are switched appropriately as the rotor rotates.

- In most BLDC motor applications requiring precise torque control, the rotor position is sensed by a Hall effect sensor, and accordingly the electronic switches of the converter are controlled to reverse currents at appropriate time instants.

Reference: Write-up on brushless DC motors.

7. DC servomotor

These motors are used in applications requiring precise control of mechanical movements (e.g., angular position). They use negative feedback with the angular position as the control variable.

Components

1. DC motor
2. Position sensor (potentiometer connected to motor shaft)
3. Feedback control (closed loop) with control electronics
4. Gearbox (for obtaining high torque and low speed)

Applications

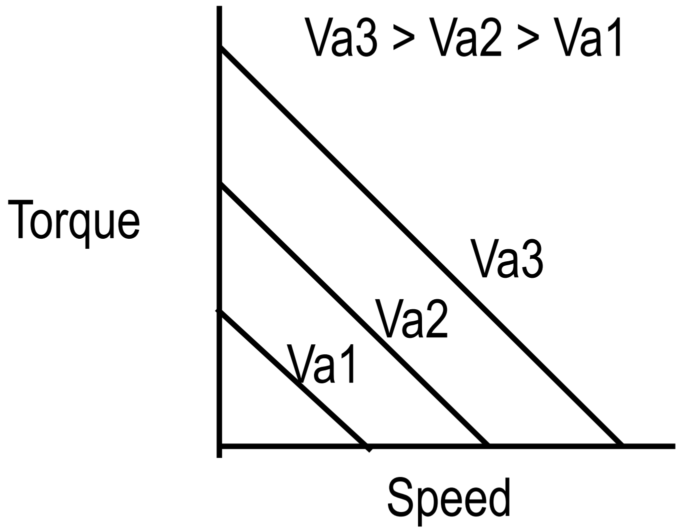
Robotics, industrial manufacturing, machine tools, packaging, printing, automatic doors, steering systems of antennas, etc.

A typical DC servomotor has 3-pins:
(i) Supply (ii) Ground, and (iii) Control (PWM)

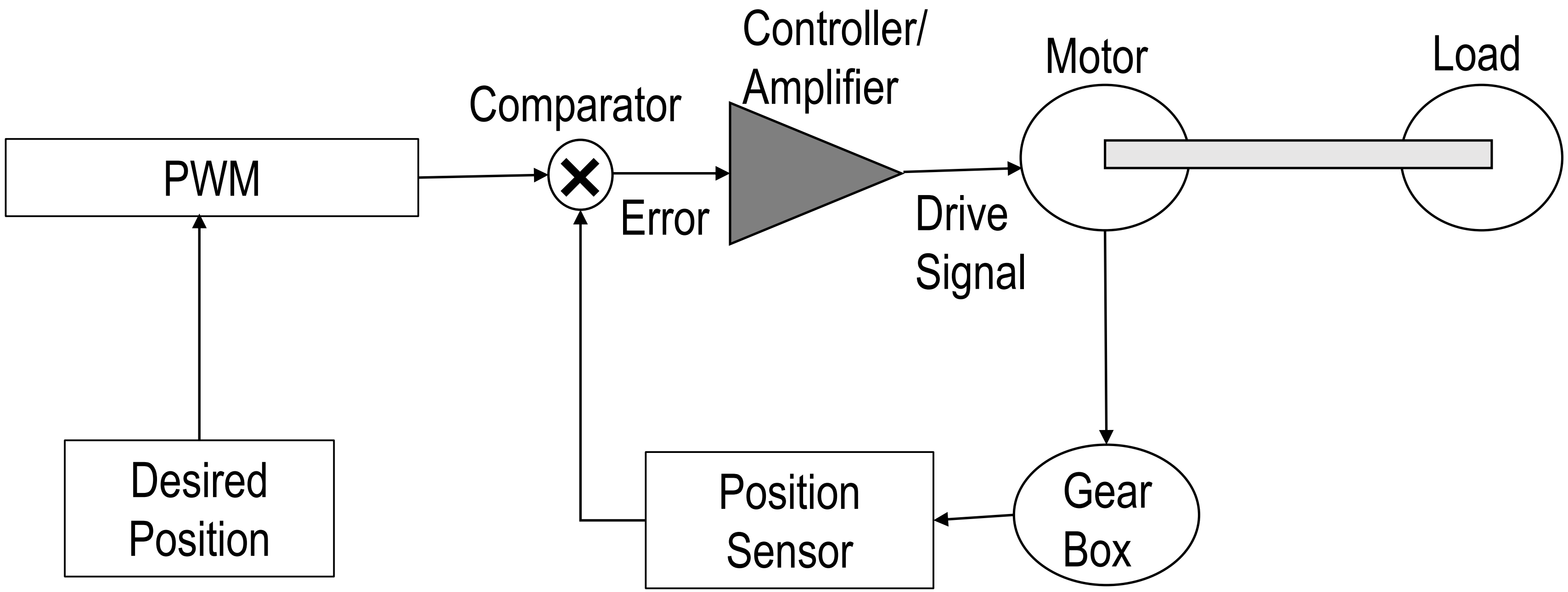
DC Servomotor Characteristics and Operation

DC motor: PMDC (brushed) or BLDC or with a separate field-coil excitation.

- High torques at low speeds (achieved through a gearbox).
- Low inertia and fast response (motor construction with small diameter and long length).
- Not designed for continuous rotation (typically designed to operate over 0 to 180 degrees in less than one second).
- PWM control applied to the armature (applied voltage, Va, is changed with a suitable duty cycle).
- High-resistance armature winding: a large negative slope in torque-speed characteristics provides viscous damping.



Servomotor Control



A servomotor is operated with closed-loop feedback with a position sensor (e.g., potentiometer).

- **The error signal depends on the difference between the actual and desired positions.**
- **The drive signal to the motor should be such that the error is eventually reduced to zero, for which either proportional (P) control, proportional and integral (PI) control, or proportional, integral, and derivative (PID) control is used.**

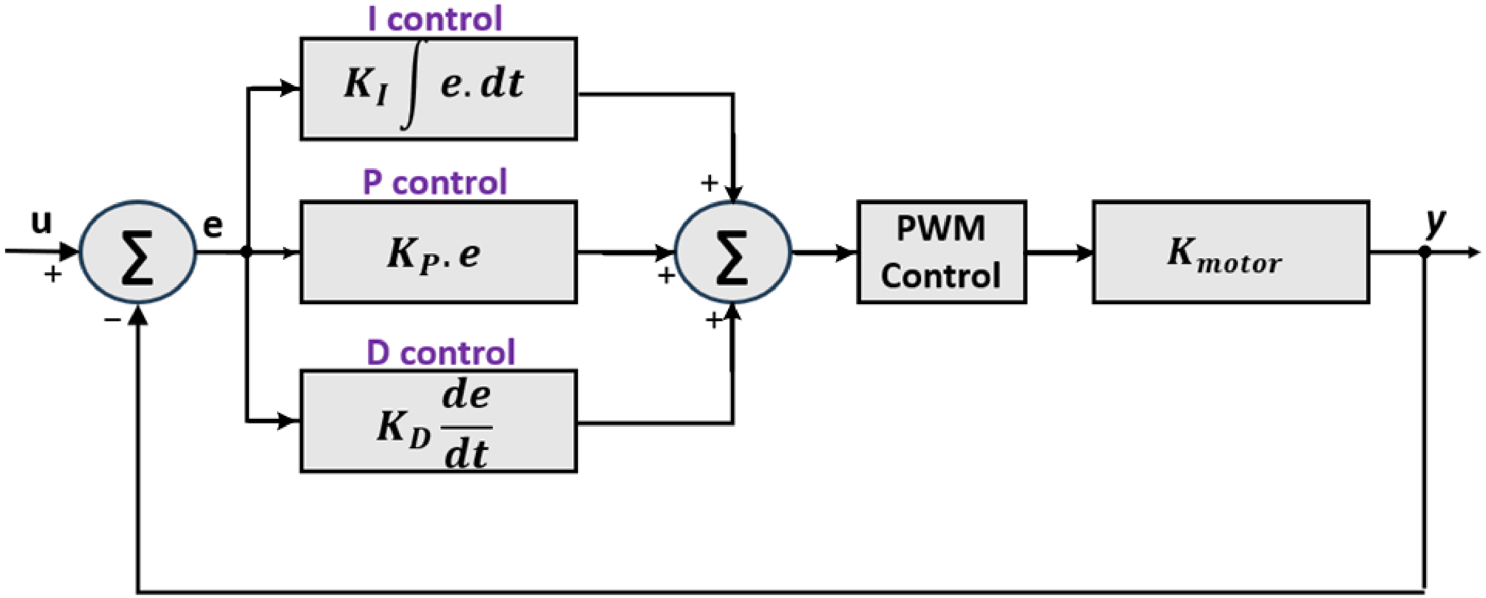
Reference: https://www.elprocus.com/dc-servo-motor/

PID Control

- P Control: $e = u - y$, controller output: $K_p\, e$.

A simple control approach, but it leads to a non-zero error.

Steady-state offset = $\frac{u}{1+Kmotor\,.\,K_p}$



- PI Control: Accumulated (integrated) error over some time is used to eliminate the offset (associated with P control). However, this control strategy results in an overshoot if the error accumulated in the initial period is high.
- PID Control: Derivative control block checks the rate of change of the error and dampens the overall gain by adding a term proportional to the negative of the rate. It helps to eliminate an overshot (if present).
- Controller gains: Depending on the system response (overshoots/ undershoots, fast/ slow response, etc.), the three controller gains need to be appropriately adjusted in a coordinated way to achieve the desired control characteristics.

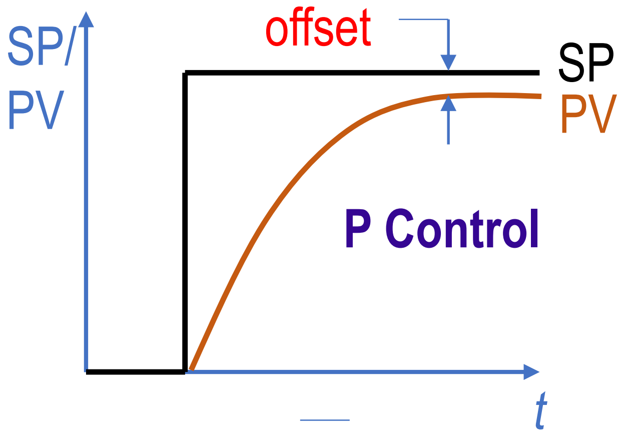
PID Control Characteristics

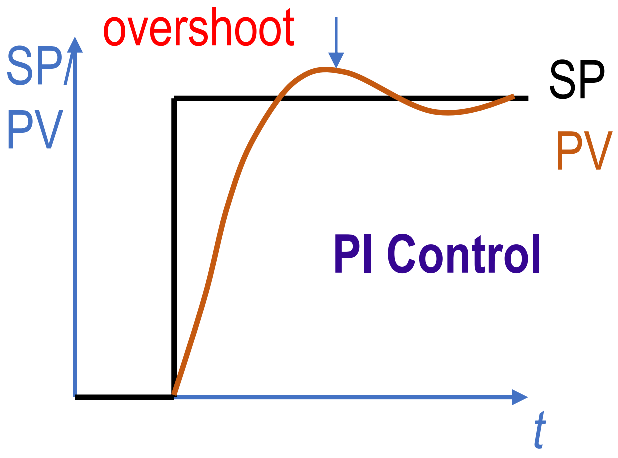
u = Set Point (SP).

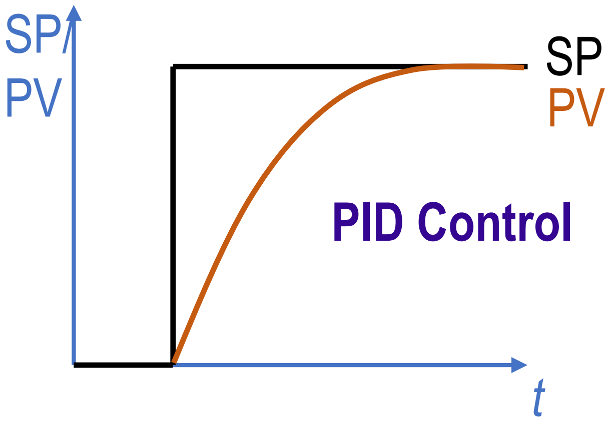
y = Process Variable (PV), speed or position.

e = error = SP − PV.

Controller gains: K_P, K_I, K_D







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