AC vs DC Motors

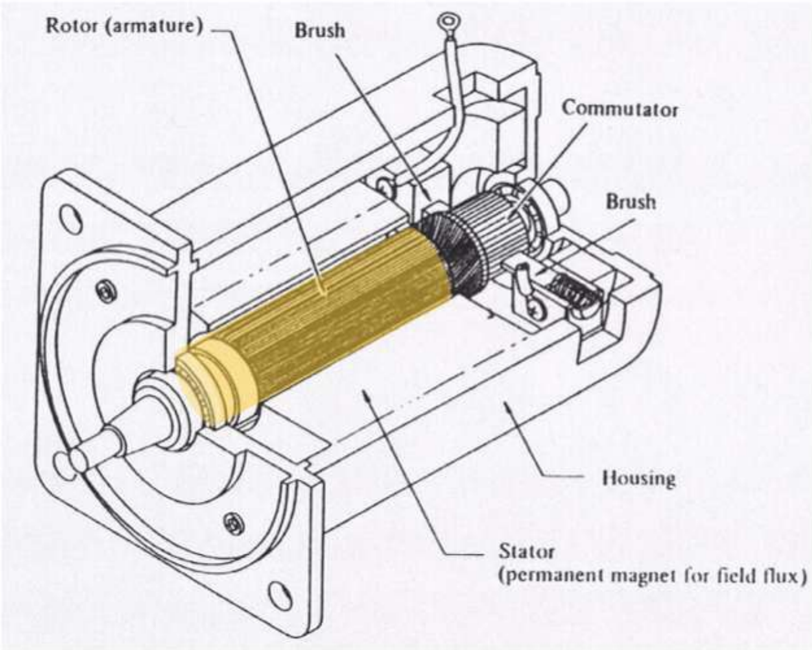
- DC Motors:
  - Pros: Simple control, inexpensive, good for ***variable speed*** applications.
  - Cons: Shorter life span, higher maintenance costs, limited to ***low power*** applications.

- AC Motors:
  - Pros: Simple design, ***high power*** factor, long life, good for ***fixed sped*** applications.
  - Cons: More complex control, poor low speed performance, poor position control.

DC Motors

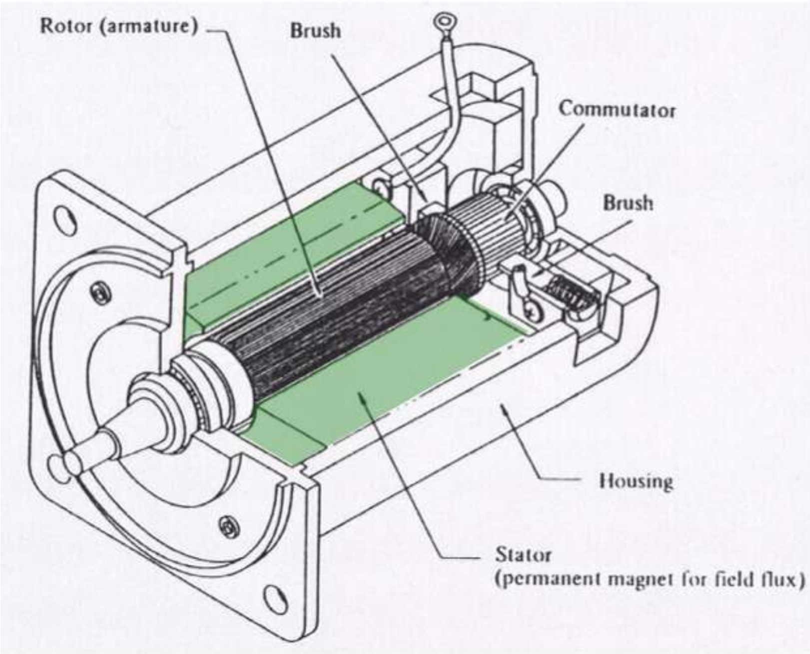
- DC motors are widely used in low power applications
- With advancements in control technology AC motors are becoming popular.
- There are two types of DC motors.
    - Brushed DC Motor: The magnetic field is generated in the stator and windings are in the rotor.
    - Brushless DC Motor: The magnetic field is generated in the rotor and windings are in the stator.

Parts of a Brushed DC Motor



- **Rotor: rotating part of the motor**
- Stator: stationary part of the motor
- Commutator: part which keeps contact with the brushes
- Brushes: part of electrical circuit through current is supplied to the armature

Parts of a Brushed DC Motor



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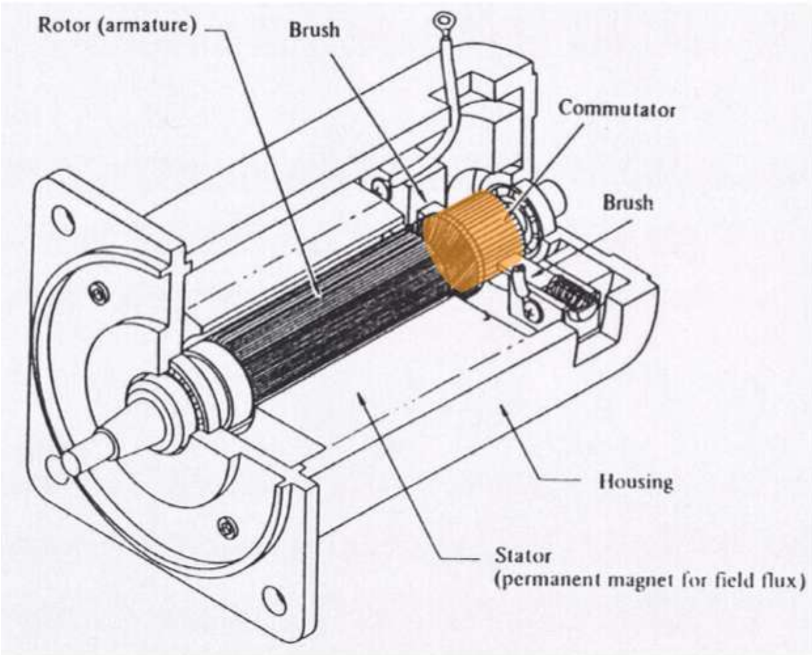
Parts of a Brushed DC Motor



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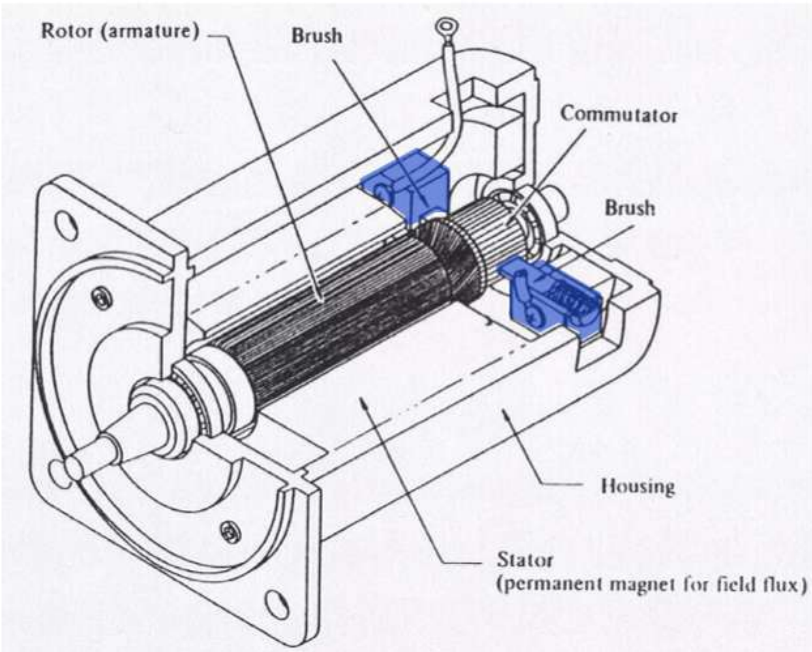
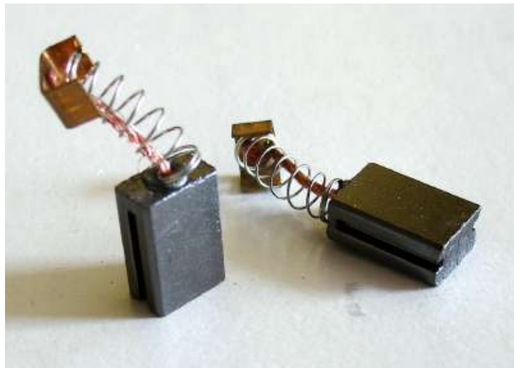
Parts of a Brushed DC Motor



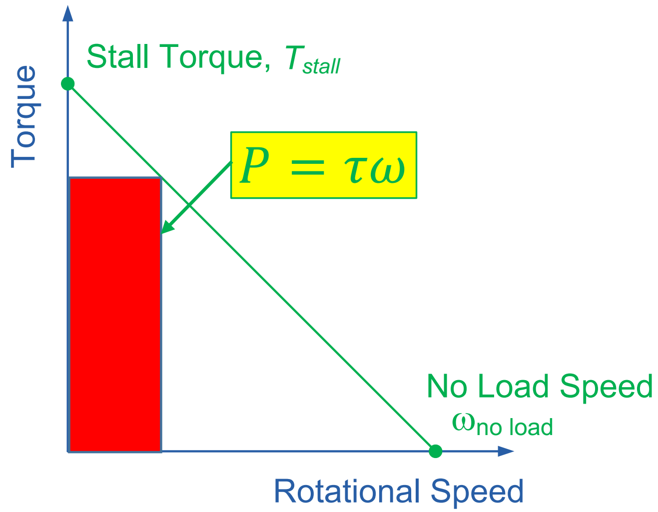
- Rotor: rotating part of the motor
- Stator: stationary part of the motor
- Commutator: part which keeps contact with the brushes
- Brushes: part of electrical circuit through current is supplied to the armature

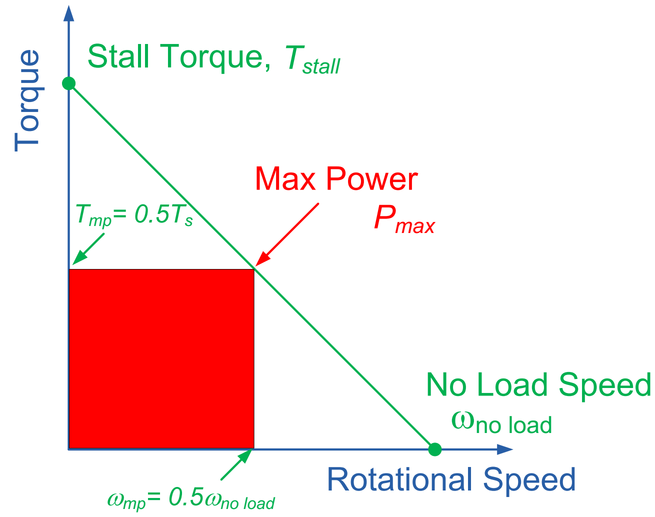
Brushes of the Motor

- Generate electrical and acoustic noise.
- Made out of different materials depending on the purpose.
  - Copper-graphite (less expensive, more current, more noise)
  - Precious metal (more expensive, less current, less noise)
- Limit maximum voltage.
- Wears out over time reducing efficiency.



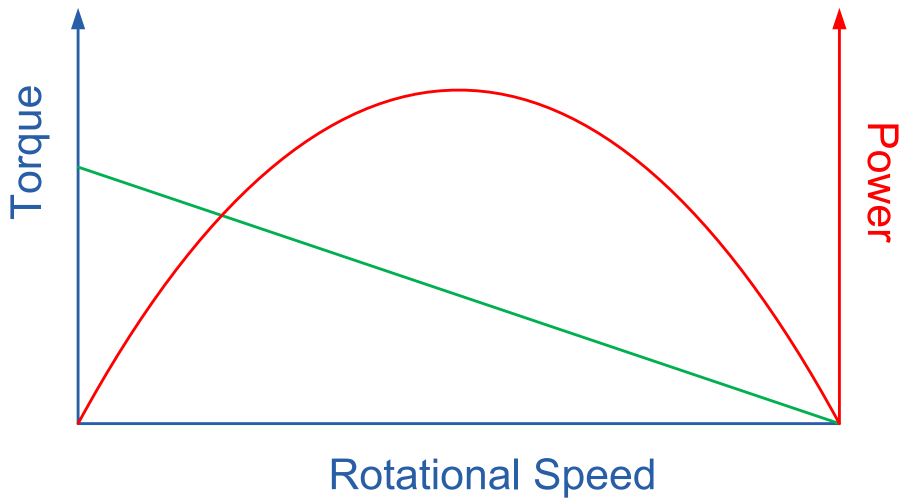
Power Delivered by the Motor





- The power delivered by the motor is given as the product of torque and angular velocity.
- This corresponds to the area of a rectangle under the torque/speed curve with one corner at the origin and another corner at a point on the curve.
- Due to the linear inverse relationship between torque and speed, the maximum power occurs at the point where $\omega = ½\ \omega_{no\ load}$, and $\tau = ½\ \tau_{stall}$.

Power curve of a DC Motor



Torque, power vs speed curve

$$P_{\text{motor}}(\omega) = -\frac{\tau_{\text{stall}}}{\omega_{\text{no load}}}\omega^2 + \tau_{\text{stall}}\omega$$

$$P_{\text{motor}}(\tau) = -\frac{\omega_{\text{no load}}}{\tau_{\text{stall}}}\tau^2 + \omega_{\text{no load}}\tau$$

The maximum output power occurs at,

$$\tau = \frac{1}{2}\tau_{\text{stall}} \quad \omega = \frac{1}{2}\omega_{\text{no load}}$$

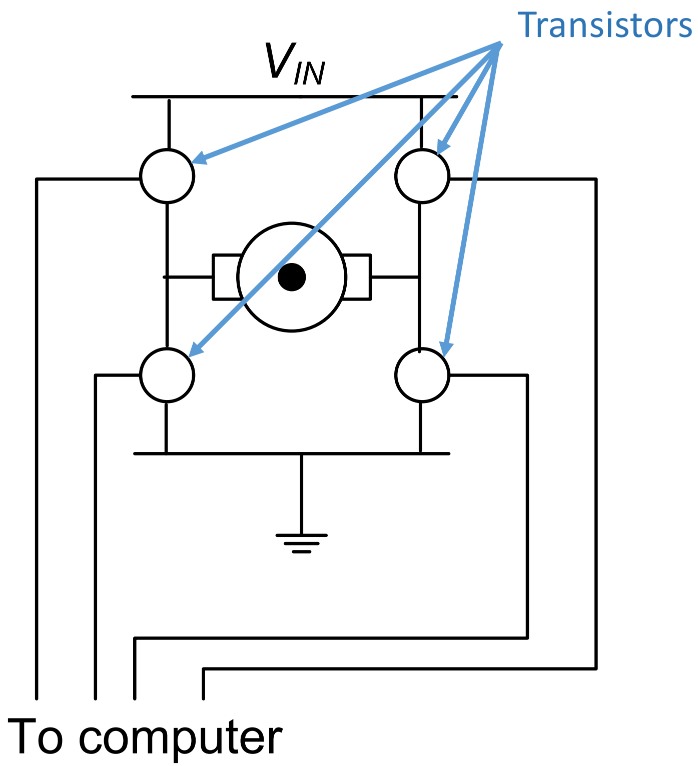
Components Required for Implementing a Controller in Hardware

- Timer Interrupt
- Obtaining Feedback
- Control Signal Calculation
- Control Signal Output

Driving a DC Motor in a Single Direction

- One of the common methods is to use a switch using an N-Channel enhancement MOSFET.
- It will supply the current and voltage required for the motors.
- Motors are significant sources of electronic noise when motors switch the supply producing significant transients on the supply.
- Optical isolation is an effective and simple solution for this.
- Therefore, opto-couplers are used to optically isolate the motor from the microcontroller or SBC without having a common supply.
- The diode shown here is used against inductive transients and called a ‘freewheeling diode’.

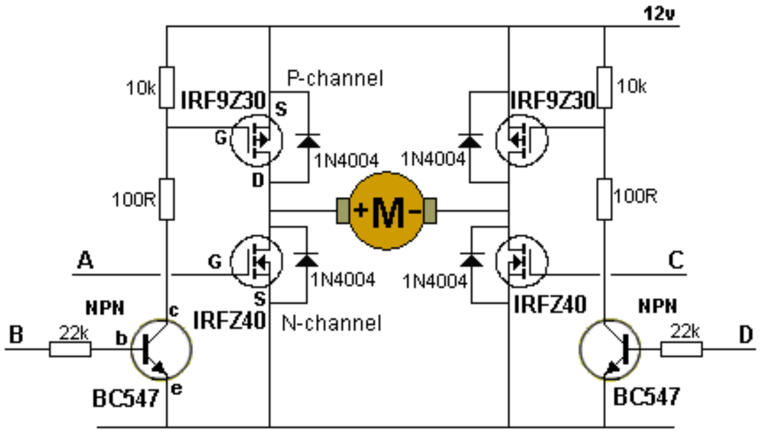
H Bridge Motor Drivers



- Name ‘H bridge’ has been derived based on the shape of the circuit.
- Four switches (usually transistors) control circuit behaviour.
- Two switches are turned on at a given time.
- Bipolar operation with unipolar voltage.
- Speed is set by input voltage.

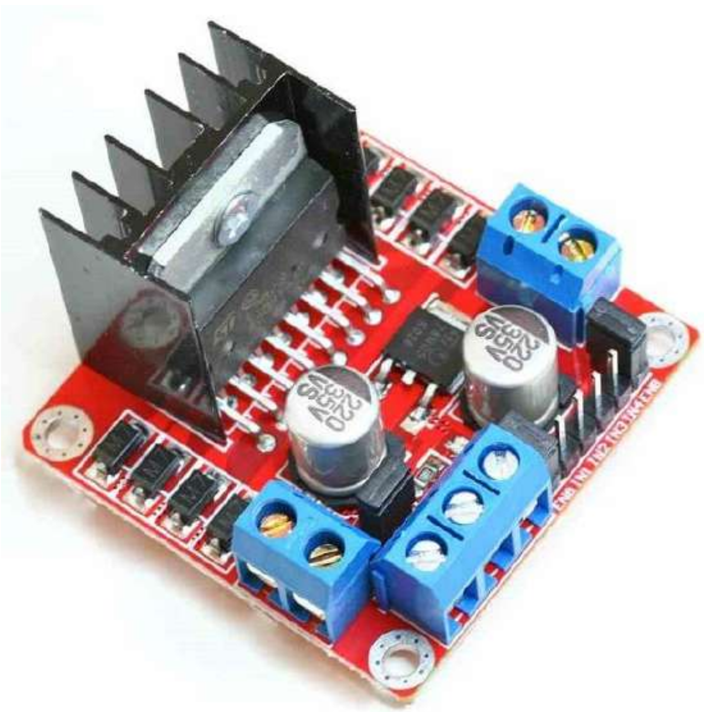
H-Bridge Motor Drivers

- An H bridge driver could be implemented using a combination of MOSFETs and transistors.



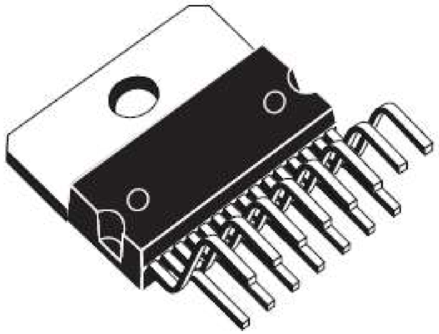
- However, there are ICs that could be used for the purpose of driving motors.

Dual H Bridge Driver

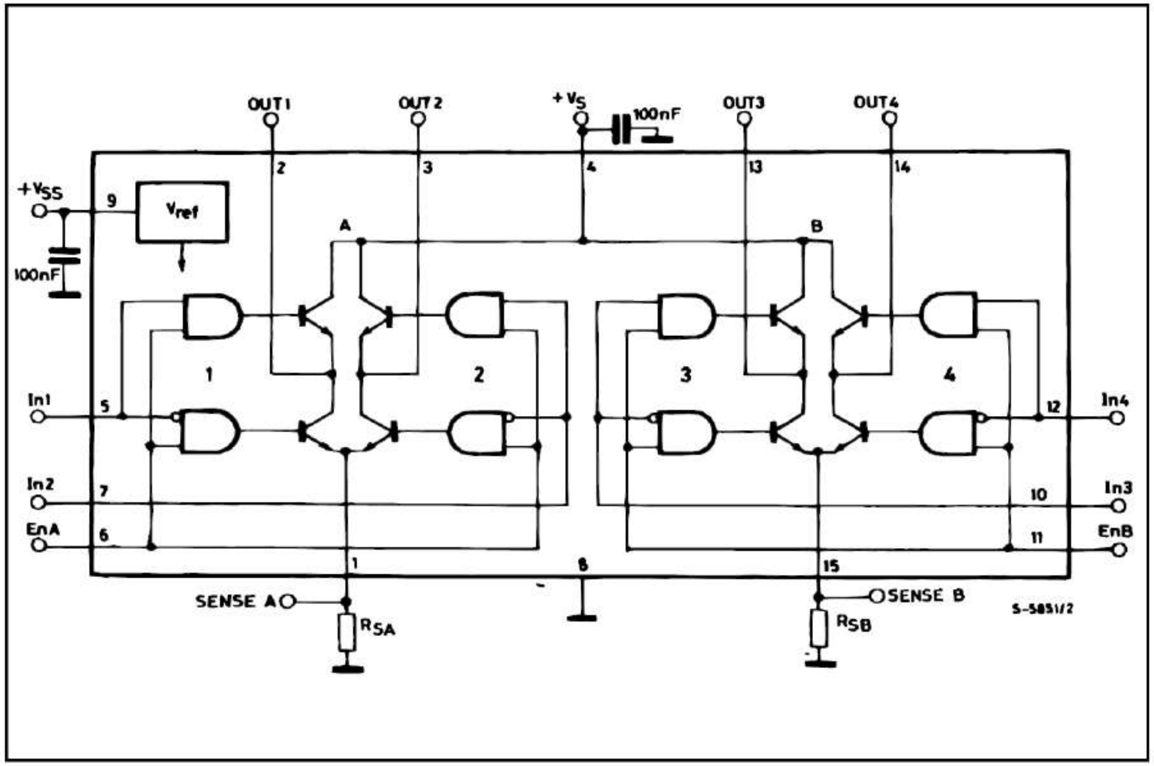


- Designed to accept standard TTL logic levels
- Supply voltage up to 46 V DC
- DC current up to 4 A
- High noise immunity
- Other temperature protection
- Could be used to run two motors simultaneously.

Schematic Diagram of the L298 H-Bridge Driver



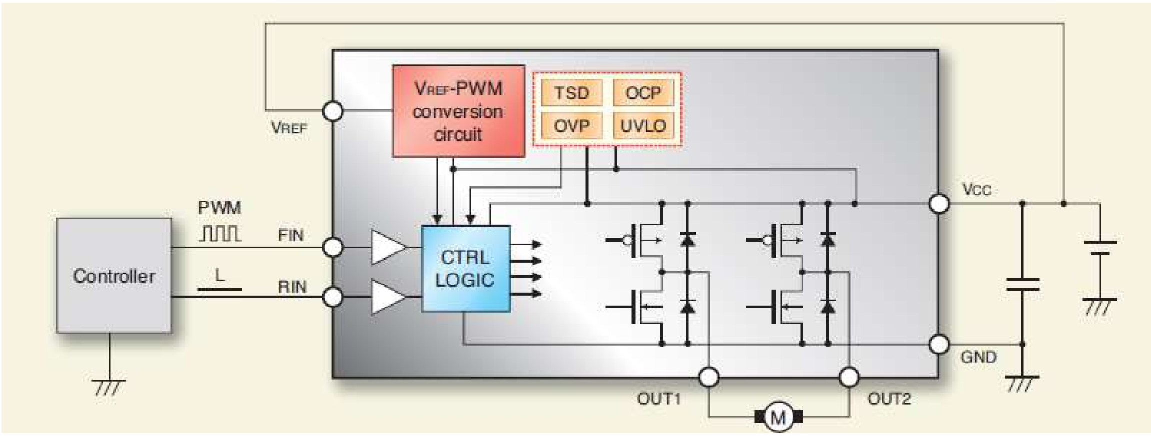
Multiwatt15



H-Bridge Motor Drivers

There are also H-Bridge driver ICs that have implemented the H drive using MOSFETs.

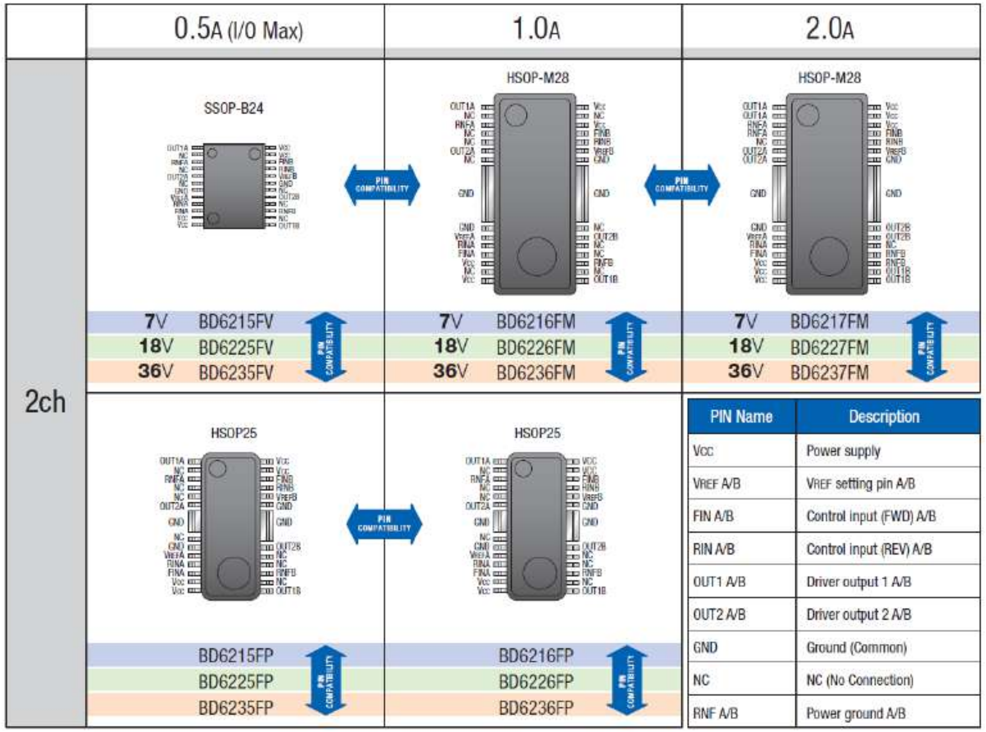
Eg: ROHM drive ICs.



Schematic Diagram of H bridge Driver IC used to control a DC Motor

Input		Output
FIN	RIN	
PWM	L	Forward
L	PWM	Reverse
H	H	Brake
L	L	Idle

H-Bridge Driver ICs from ROHM



PIN Name	Description
Vcc	Power supply
VREF A/B	VREF setting pin A/B
FIN A/B	Control input (FWD) A/B
RIN A/B	Control input (REV) A/B
OUT1 A/B	Driver output 1 A/B
OUT2 A/B	Driver output 2 A/B
GND	Ground (Common)
NC	NC (No Connection)
RNF A/B	Power ground A/B

DC Motor Types

Brushed DC

Advantages

- Cheapest and simplest motor
- Speed linear to applied voltage
- Simple motor control

Disadvantages

- High maintenance
- Low life-span (due to physical wear on brushes)

Brushless DC

Advantages

- High efficiency
- Little to no maintenance
- Long life span
- High output power per frame size

Disadvantages

- More complicated motor control
- Large initial costs

Stepper

Advantages

- Accurate position control
- Excellent low speed torque
- Long life

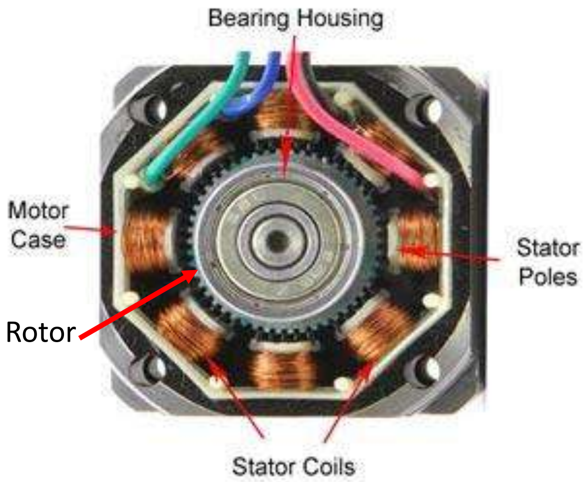
Disadvantages

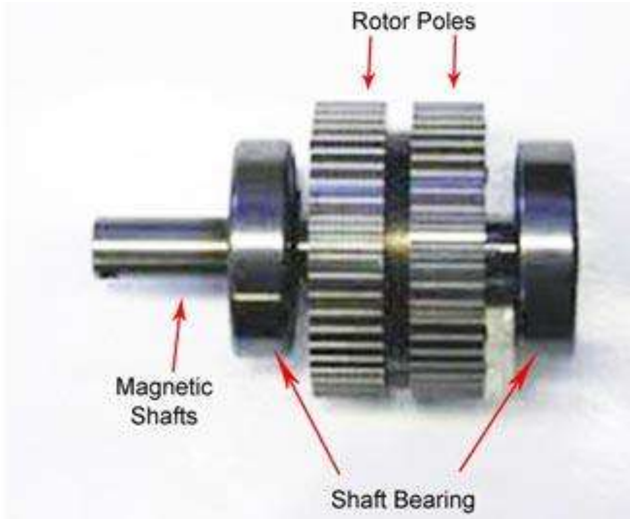
- Low efficiency
- Prone to resonances, noise, and torque ripple
- Cannot accelerate loads rapidly

Stepper Motors

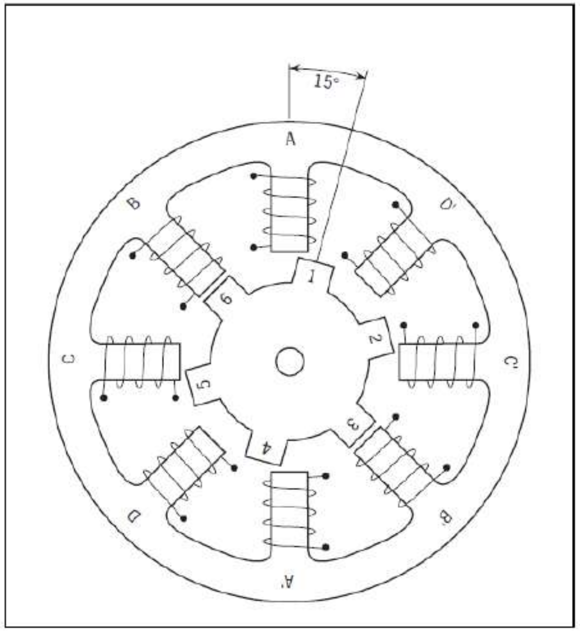
- Stepper motors consist of a rotor which consists of a permanent magnet as the rotor and wound coils as the stator.
- These are similar to brushless DC motors but move in discrete steps.
- Stepper motors have multiple coils that are organized in groups called "phases".
- By energizing each phase in sequence, the motor will rotate, one step at a time.
- The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor.
- This makes these motors useful for some of the applications.

A Cross Section of a Hybrid Stepper Motor





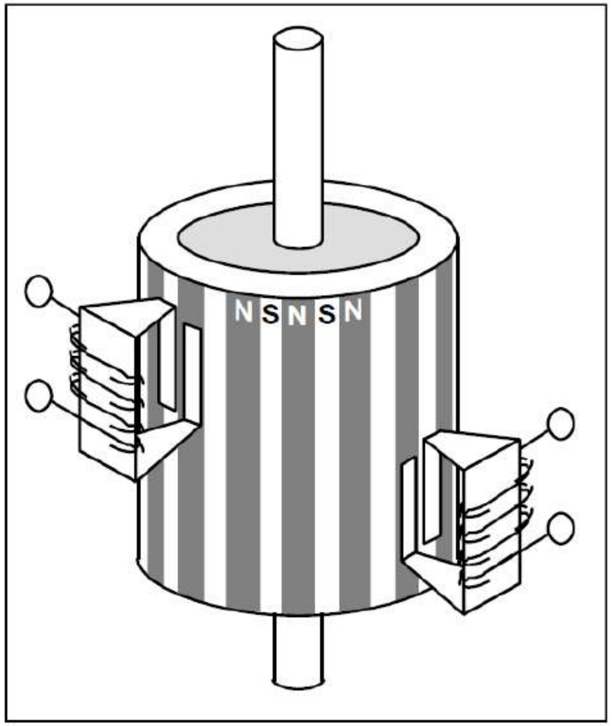
Types of Stepper Motors (1)



Variable Reluctance Motor:

- This motor consists of a soft iron multi-toothed rotor and a wound stator.
- When the stator windings are energized with DC current the poles become magnetized.
- Rotation occurs when the rotor teeth are attracted to the energized stator poles.

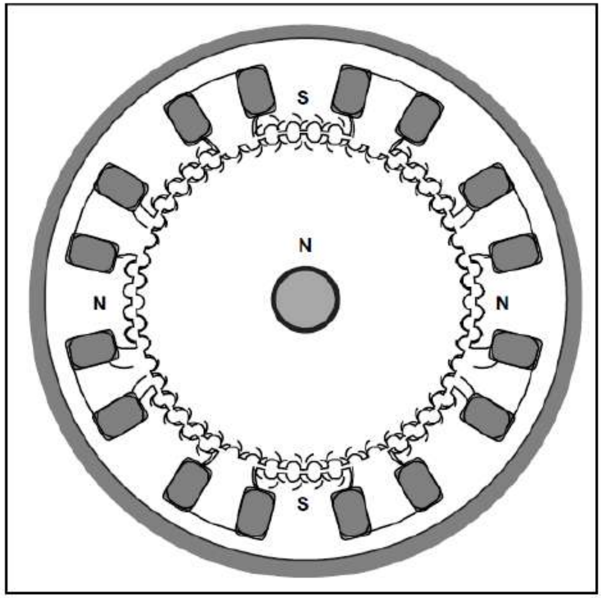
Types of Stepper Motors (2)



Permanent Magnet Motor

- The PM motor has permanent magnets added to the motor structure.
- This is a low cost / low resolution type motor with typical step angles of 7.5° to 15°.
- The rotor has no teeth as compared to the VR motor.
- The rotor is magnetized with alternating north and south poles situated in a straight line parallel to the rotor shaft.
- The magnetized rotor poles provide increased magnetic flux intensity hence improved torque characteristics.

Types of Stepper Motors (3)

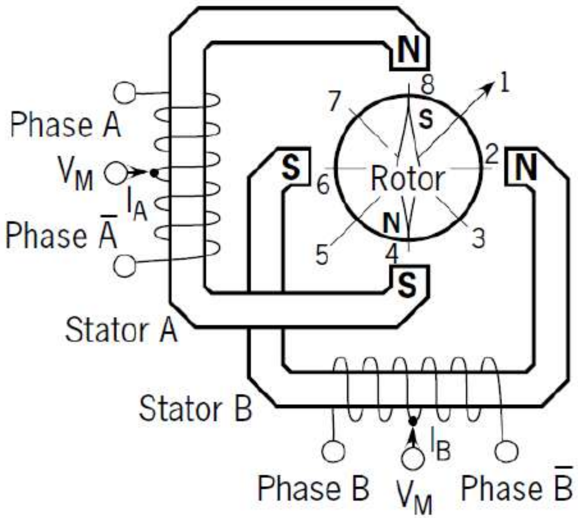


Hybrid Stepper Motor

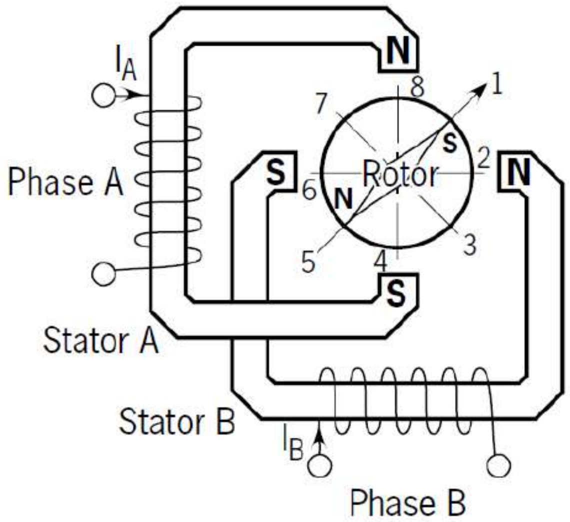
- The hybrid stepper motors combine the best features of PM and VR type stepper motors.
- The hybrid stepper provides a better performance with respect to step resolution, torque and speed.
- Typical step angles range from 3.6° to 0.9° (100 – 400 steps per revolution).
- The rotor is multi-toothed and contains an axially magnetized concentric magnet around its shaft.
- The teeth on the rotor provide a better path which helps guide the magnetic flux to preferred locations in the airgap.

Bipolar and Unipolar Stepper Motors

Unipolar Stepper Motor

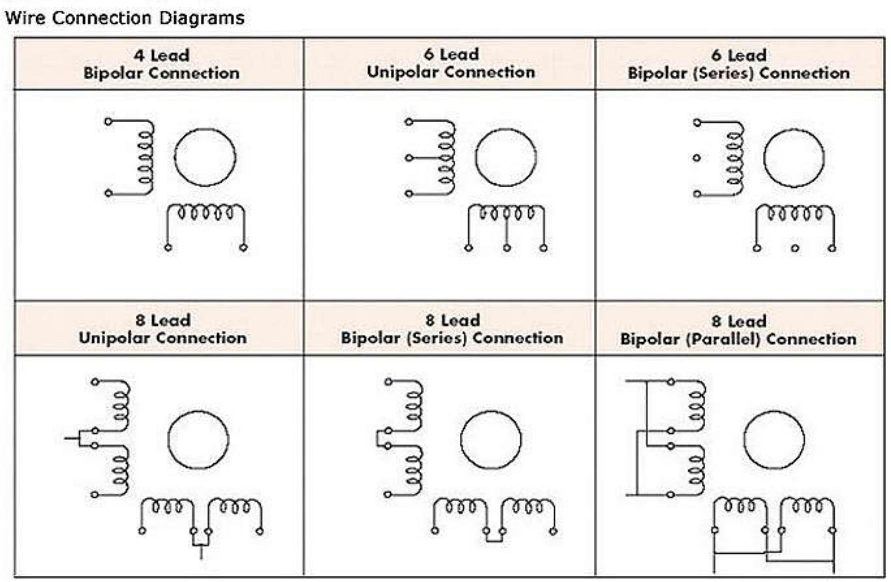


Bipolar Stepper Motor



- Motors could be divided based on the construction of the stator winding.
- These are,
  - Bipolar stepper motors – Has two phases with one winding/phase .
  - Unipolar stepper motors – Has two phases with one winding/phase and a center tap.

Stepper Motor Windings



- Usually stepper motors have two phases, but three- and five-phase motors also exist.
- Sometimes the unipolar stepper motor is referred to as a “four phase motor”, even though it only has two phases.
- Motors that have two separate windings per phase also exist—these can be driven in either bipolar or unipolar mode.

Stepper Motor Torque

- The torque output produced by the motor is proportional to the intensity of the magnetic flux generated when the winding is energized.
- This relationship shows that the magnetic flux intensity and consequently the torque is proportional to the number of winding turns and the current and inversely proportional to the length of the magnetic flux path.
- The basic relationship which defines the intensity of the magnetic flux is defined by:

$$H = (N \times i) / l$$

N = The number of winding turns

i = current

H = Magnetic field intensity

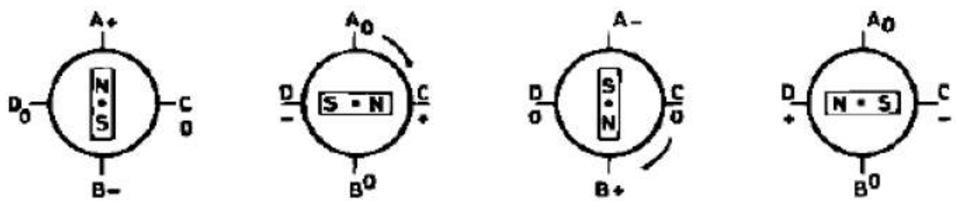
l = Magnetic flux path length

Stepper Motor Drive Modes

- The following are the most common drive modes.
  - Wave Drive
  - Full Step Drive
  - Half Step Drive
  - Microstepping

Wave Drive Mode

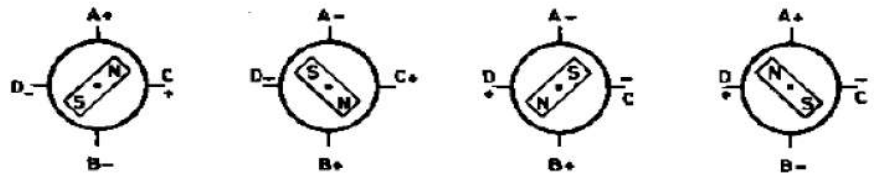
- Only one pole is energised at a given time.



Stepper Motor Drive Modes

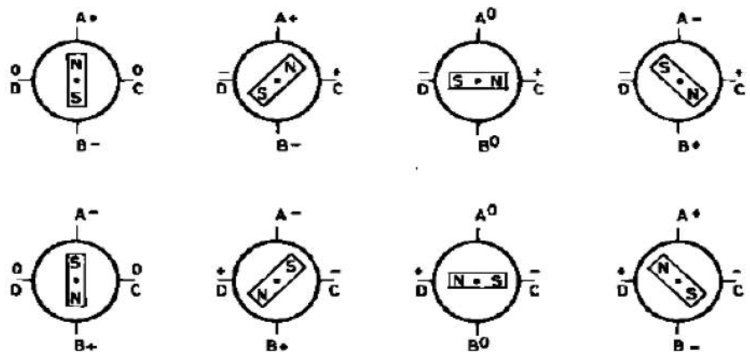
Full Step Drive Mode

- Two poles are energised at a given time.



Half Step Drive Mode

- One or Two poles are energised at a given time.

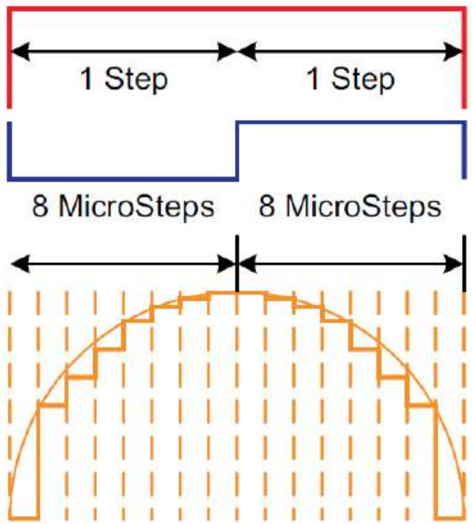


Microstepping Mode (1)

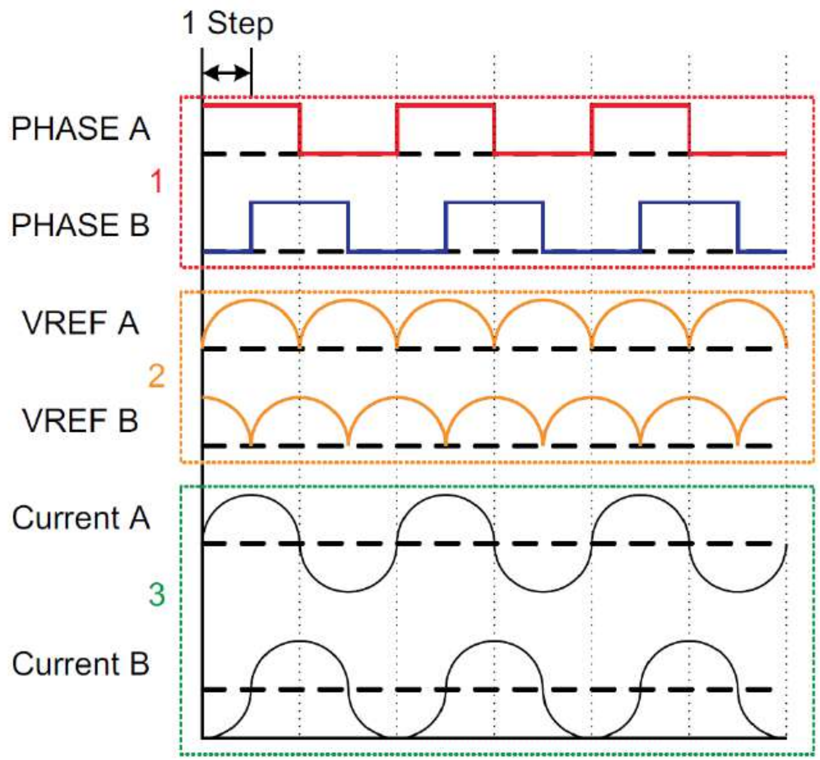
- Microstepping is a way of moving the stator flux of a stepper motor more smoothly than in full- or half- step drive modes.
- It results in less vibration, and makes noiseless stepping possible down to 0 Hz making smaller step angles and better positioning possible.
- There is a number microstepping modes, with step lengths from 1⁄3 full-step down to 1⁄32 full step or even less.
- In microstepping the winding current approximates a sinusoidal AC waveform.
- Sine cosine microstepping is the most common form, but other waveforms can be used.
- Regardless of the waveform used, as the microsteps become smaller, motor operation becomes more smooth

Microstepping Mode (2)

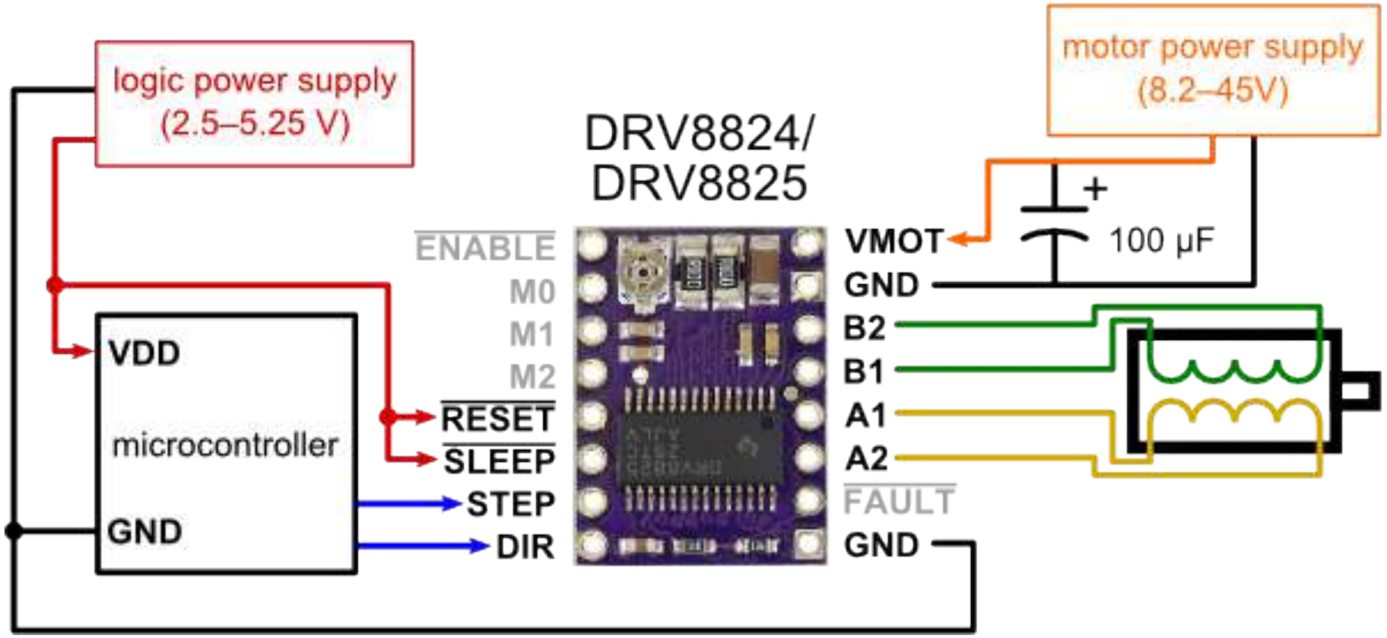
- Possible resolution will be limited by the mechanical stiction, backlash, and other sources of error between the motor and the end device.
- Microstep division of a full step.



Microstepping Mode (3)



Stepper Motor Drivers



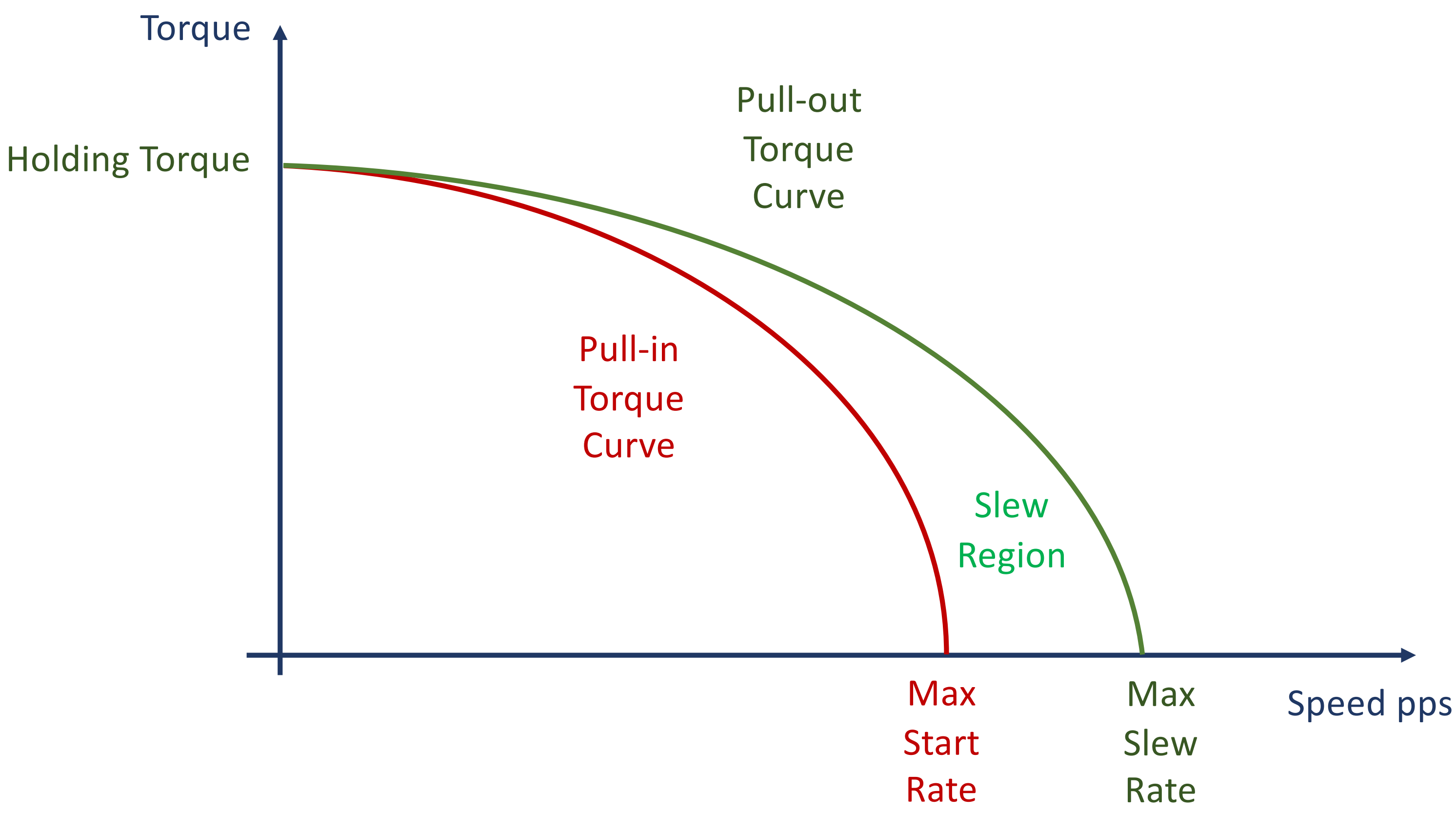
Stepper Motor Size

- Stepper motors are also classified according to the frame size by the US National Electrical Manufacturers Association.
- These are referred to as NEMA standards.
- The NEMA standards refer to frame sizes that correspond to diameter of the motor frame.
- For instance NEMA11 stepper motor has a body diameter of approximately 1.1 inches. Likewise, NEMA23 stepper motor has a body diameter of 2.3 inches (58 mm).
- The body length may vary from motor to motor within the same frame size classification.
- As a general rule the available torque output from a motor of a particular frame size is increased with body length.

Stepper Motor Torque

- Full step drive mode produces a higher torque because two poles are energized at a given time.
- Half step drive model produces a higher resolution as compared to full step drive mode.
- The torque produced by a stepper motor depends on several factors.
  - The step rate
  - The drive current in the windings
  - The drive design or type

Stepper Motor Torque vs Speed Curve



Pull-in torque

- It is known as starting torque.
- This is the torque produced by a stepper motor when it starts to rotate from standstill.
- This is the maximum speed at which the motor can start or stop instantaneously, with a load applied, without skipping steps or synchronism.
- The pull in torque is basically used to overcome friction and inertia.

Pull-out torque

- The stepper motor pull-out torque is measured by accelerating the motor to the desired speed and then increasing the torque loading until the motor stalls or when it starts to skip steps.
- This pullout torque is calculated across a range of speeds and the stepper motor's dynamic performance curve is generated.
- This dynamic performance curve is useful when the motor is used for applications require accelerating and decelerating.

Detent torque

- Electric motors using permanent magnets have a remnant position holding torque when these are not driven electrically.
- This detent torque is very useful for some of the applications as the motor continues to apply a torque even then the current is disconnected.

Holding torque

- This is the maximum torque produced when the motor is at a standstill.

Maximum start rate

- This is the maximum no-load speed the motor can achieve from a standing start.

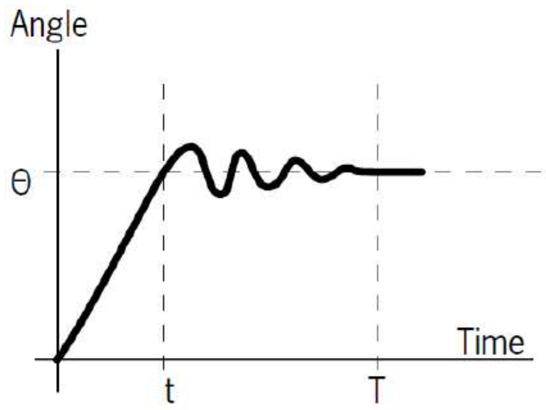
Maximum slew rate

- This is the maximum speed which the motor can achieve. This is the highest no load speed which the motor could accelerate without skipping steps.

Slew Region

- Slew region defines the usual operating region of a stepper motor. At this region it will operate without skipping steps

Transient Response of a Stepper Motor



- When a single step pulse is applied the rotor, it behaves as given by the curve shown above.
- The step time ***t*** is the time it takes the motor shaft to rotate one step angle once the pulse is applied.
- This step time is highly dependent on the ratio of torque to inertia (load) as well as the type of driver used.
- There is a resonance area around the 100 – 200 pps region and also one in the high step pulse rate region.

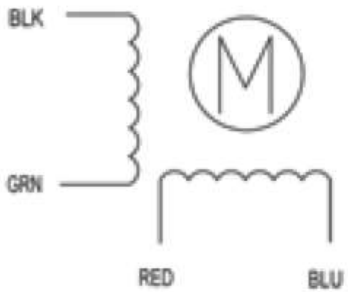
Motor Power

- Power levels for IC-driven stepper motors typically range from between 1-20 W.
- The maximum power dissipation level or thermal limits of the motor are seldom clearly stated in the motor manufacturers data.
- To determine this we must apply the relationship P = VI.
- For example, if a two phase stepper motor is rated at 6 V and 1 A per phase, the rated power dissipation of the motor is 6 x 1 x 2 = 12 Watts.
- It is the normal practice to rate a stepper motor at the power dissipation level where the motor case rises 65°C above the ambient in still air.
- If it is continuously operated for a long time, a heat sink should be used for maximum power dissipation, so that it is efficient from a size/output, power/cost point of view.

Stepper Motor Ratings

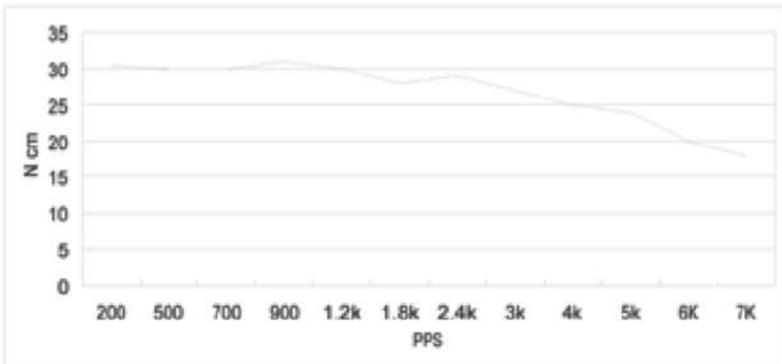
General specifications		Electrical specifications	
Step Angle (°)	1.8	Rated Voltage (V)	2.8
Temperature Rise (°C)	80 Max (rated current 2 phase on)	Rated Current (A)	1.68
Ambient temperature (°C)	-20～+50	Resistance Per Phase (±10%Ω)	1.65 (25°C)
Number of Phase	2	Inductance Per Phase (±20%mH)	2.8
Insulation Resistance	100MΩ, Min (500VDC)	Holding Torque (Kg.cm)	4.4
Insulation Class	Class B	Detent Torque (g.cm)	200
Max.radial force (N)	28 (20mm from the flange)	Rotor Inertia (g. cm²)	68
Max.axial force (N)	10	Weight (Kg)	0.365

● Wiring Diagram:



● Pull out torque curve:

VOLTAGE: 24VDC, CONSTANT CURRENT: 1.68A, HALF STEP



When to Use a Stepper Motor

- A stepper motor can be a good choice whenever controlled movement is required.
- It provides simple open loop controlled motion.
- Stepper motors could be used to advantage in applications where it requires to control the rotation angle, speed, position and synchronism.
- Because of the inherent advantages listed previously, stepper motors could be used for several different applications.
- Some of these include printers, plotters, high end office equipment, hard disk drives, medical equipment, fax machines, automotive and many more.

Advantages and Disadvantages of Stepper Motors

Advantages

1. The rotation angle of the motor is proportional to the number of input pulses.
2. The motor has the highest torque at standstill (if the windings are energized).
3. Precise positioning and repeatability of movement.
4. Excellent starting/stopping/reversing response.
5. Very reliable since there are no contact brushes in the motor.
6. Provides open-loop control with a series of digital pulses.

Disadvantages

1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds.

Conclusions

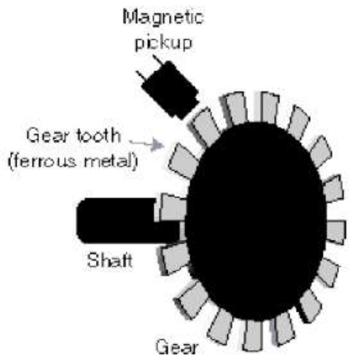
- The two most commonly used types of stepper motors are the permanent magnet and the hybrid types.
- Possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
- A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.
- Many modern hybrid step motors can produce 200 full steps per revolution or 1.8 degrees per full step.
- The accuracy of the stepper motor will be within 3% or 5% of the travel of every other full step, as long as the motor is operated within its specified operating ranges.

Encoders

- Converts a position change to a series of digital signals.
- The resolution of encoder depends upon the number of pulses in a specified direction.
- Only one channel is required if measurement is carried out in one direction.
- Two channels are required if measurement is carried out in both directions.

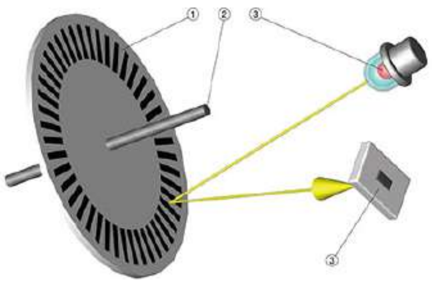
Pulse Technology

- Magnetic



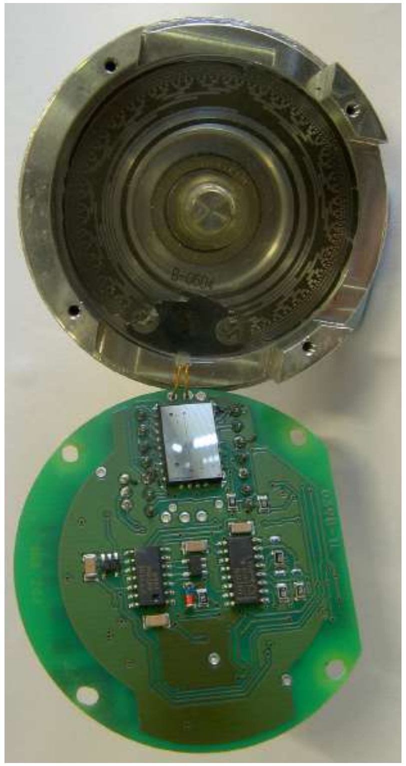
- Switch Contacts

- Optical Reflective



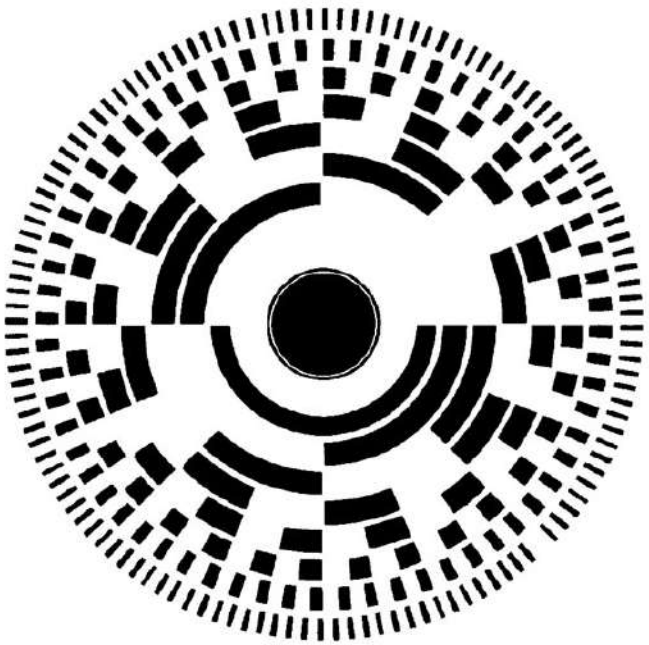
- Optically Transmissive

Absolute Encoders



- In absolute encoders each position is provided using a unique code.
- This is often based on a Gray code, where the codes for adjacent positions differ by at most 1 bit.
- These encoders are more complicated to work with.
- Always exact position is known.
- Provides limited resolution.

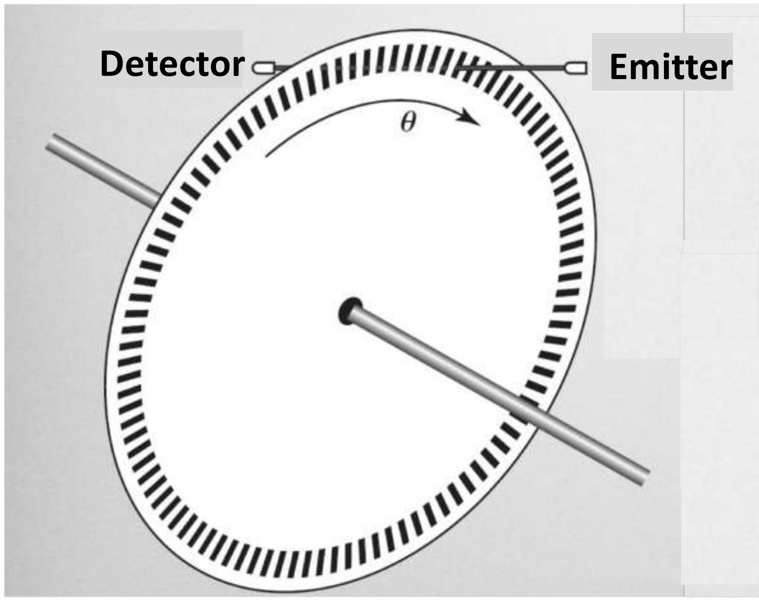
Absolute Encoders



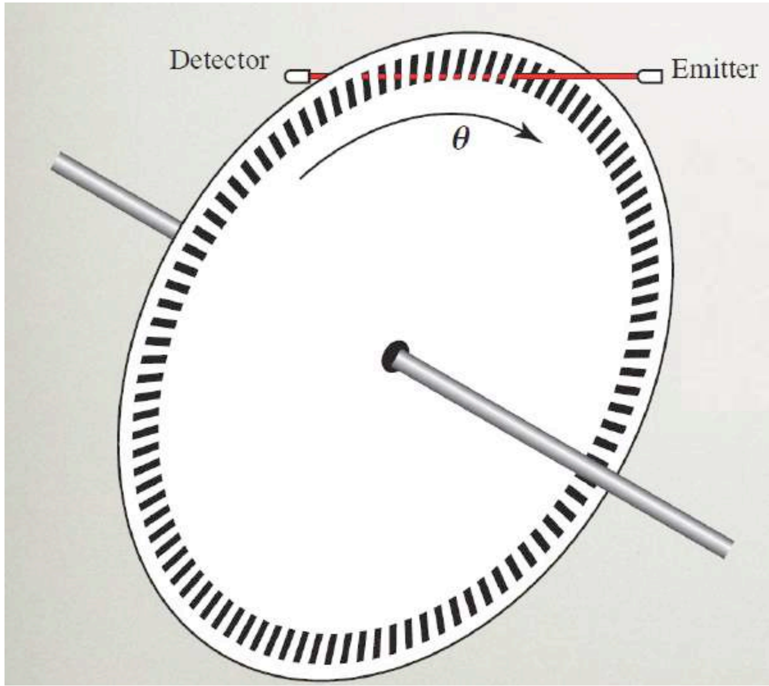
- An 8 bit absolute encoder disc is shown as an example.
- Each ring corresponds to a bit.
- The number of pulses per revolution is 2^8 = 256.
- Therefore, it requires 8 channels.
- These encoders can only produce 1x decoding.
- The start up position should always be known at the beginning.
- Should use gray code decoding for angular position.

Optical Encoders

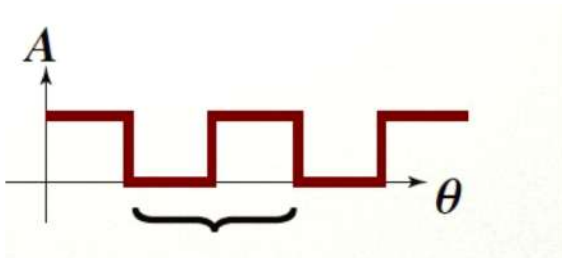
- These encoders have a slotted wheel with an emitter and detector.
- When the slotted wheel rotates the emitter will receive a series of pulses.
- Using these pulses the angular position could be calculated.



Single Directional Encoding



- Number of Pulses per Revolution(PPR): *N*



1x Resolution: 360°/*N*

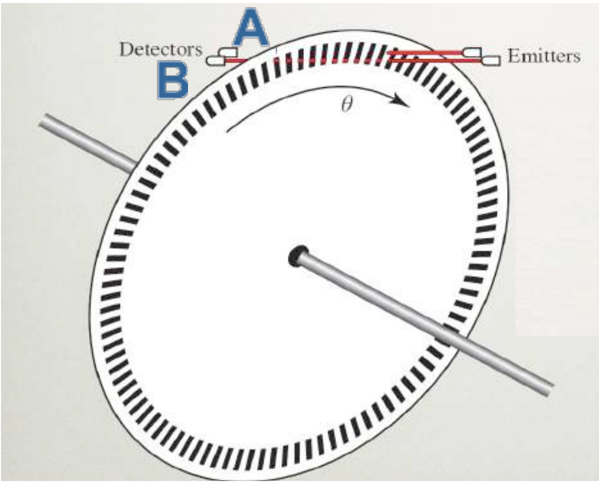
2x Resolution: 180°/*N*

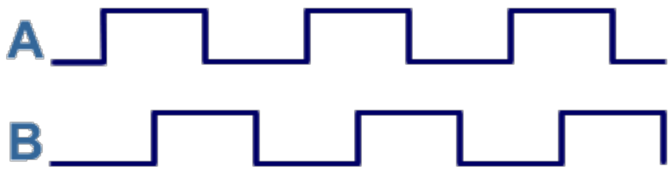
Single Directional Encoding

- By counting the number of pulses it produces a resolution that is same as the number of slots (1x).
- By counting the number of transitions it produces a resolution that is twice as the number of slots (2x).
- The counting can be done by a microcontroller or SBC by either:
  - Polling the channel.
  - Using a channel to trigger interrupts.

Bi-Directional Encoding

- By simply using a single set of emitters and receivers the number of pulses could be obtained.
- In order to find the direction a second emitter/receiver set is required.
- The second emitter/receiver set is placed 90^o out of phase with the first one.





Timer Interrupts

- Interrupt means event, which invites attention of the processor on occurrence of some action at hardware or software interrupt instruction event.
- In response to the interrupt, the routine or program, which is running presently interrupts and an interrupt service routine (ISR) executes.
- ISR is also called device driver in case of the devices and called *exception or signal or trap handler* in case of software interrupts
- Processor executes the program, called interrupt service routine or signal handler or trap handler or exception handler or device driver, related to input or output from the port or device or related to a device function on an interrupt and does not wait and look for the input ready or output completion or device-status ready or set.

Hardware Interrupts

- When a device or port is ready, a device or port generates an interrupt, or when it completes the assigned action or when a timer overflows or when a time at the timer equals a preset time in a compare register or on setting a status flag (for example, on timer overflow or compare or capture of time) or on click of mice in a computer
- Hardware interrupt generates call to an ISR

Software Interrupts (1)

- When software run-time exception condition (for examples, division by 0 or overflow or illegal opcode detected) the processor-hardware generates an interrupt, called *trap, which calls an ISR*
- When software run-time exception condition defined in a program occurs, then a software instruction (SWI) is executed– called *software interrupt* or *exception or signal, which calls an ISR* .
- When a device function is to be invoked, for example, *open* (initialize/configure) or *read* or *write* or *close* , then a software instruction (SWI) is executed– called *software interrupt* to execute the required device driver function for open or read or write or close operations.

Software Interrupts (2)

- Software can execute the software instruction (SWI) or Interrupt *n* (INT *n*) to *signal* execution of ISR (interrupt service routine). The *n* is as per the handler address.
- *Signal* interrupt [The *signal* differs from the function in the sense that execution of signal handler (ISR) can be masked and till mask is reset, the handler will not execute on interrupt. Function on the other hand always executes on the call after a call-instruction.]