Lecture 17: Actuators 3

ME/AE 6705

Introduction to Mechatronics

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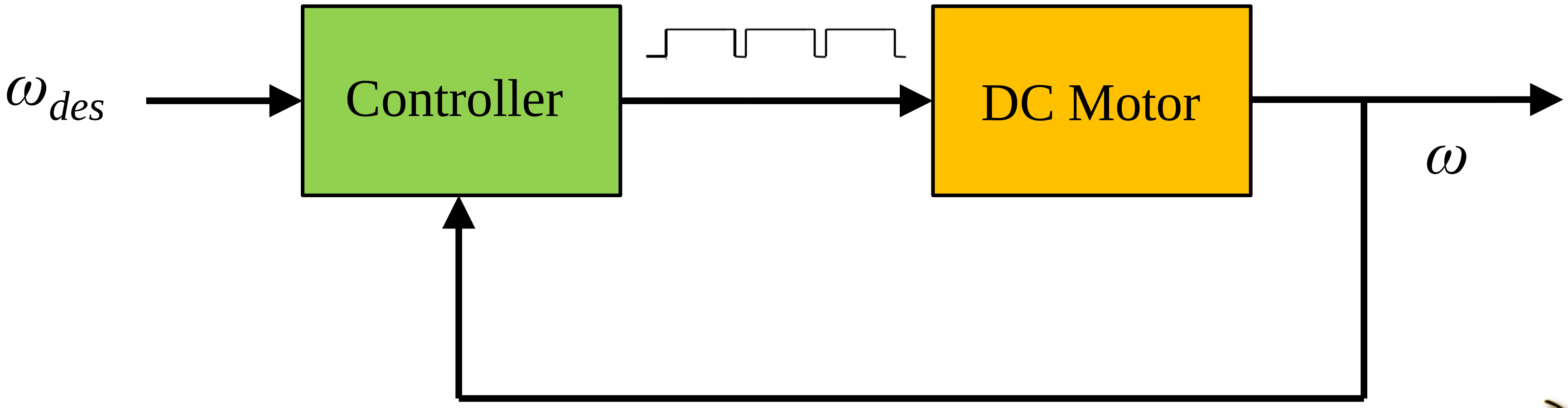
Lesson Objectives

- Become familiar with construction and operation of stepper motors
  - Be able to explain the difference between unipolar and bipolar stepper motors
  - Become familiar with stepper motor specifications (holding torque, etc)
- Be able to control a stepper motor using a MCU and H-bridge

Stepper Motors

- DC motors are useful when we try to drive a load at a given speed
  - Simple to incorporate speed sensor and use as feedback to PWM signal



Stepper Motors

- What if we want to drive a load to a specific angular position, rather than a specific angular velocity?
  - More difficult to do this using pure speed control of a motor since we need an integrator or absolute encoder
  - DC motors not designed to operate for long periods of time at stall torque
- Stepper motors are special type of DC motor that is meant for precise positioning
  - Used in many industrial applications

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Stepper Motors

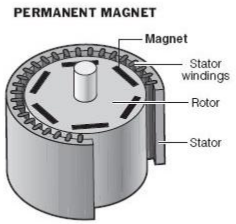
- Four key features of stepper motors:
  1. Under normal operations, motor position can be controlled precisely without additional sensors just by maintaining rotation count
  2. Only require two input signals: Direction signal and Pulse signal
  3. No wires connected to rotor (same as BLDC)
  4. Generate large torque at low speed (no need for gears)

Stepper Motor Types

- Stepper motors come in three types (differ in construction of the rotor)

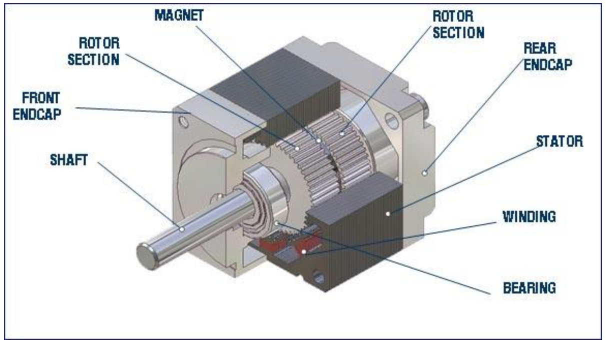
Permanent Magnet (PM) Stepper Motor

- Rotor is permanent magnet, does not use teeth
- Can provide small holding torque



Variable Reluctance (VR) Stepper Motor

- Rotor is non-magnetic, uses teeth to achieve finite step size
- Faster dynamic response



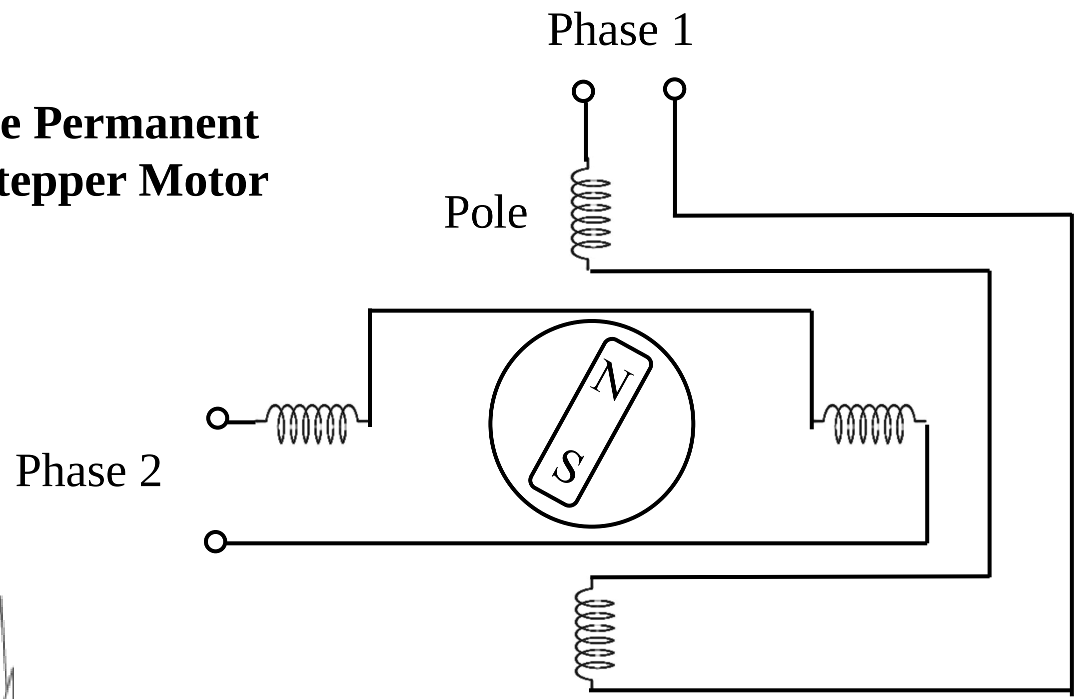
Hybrid Stepper Motor

- Has magnetic rotor and uses teeth
- Most widely used in industrial applications

PM Stepper Motor Operation

- Construction similar to BLDC motor
  - Phase: A set of coil windings
  - Pole: Magnetic field orientation induced by current through coil

Two-Phase Permanent Magnet Stepper Motor

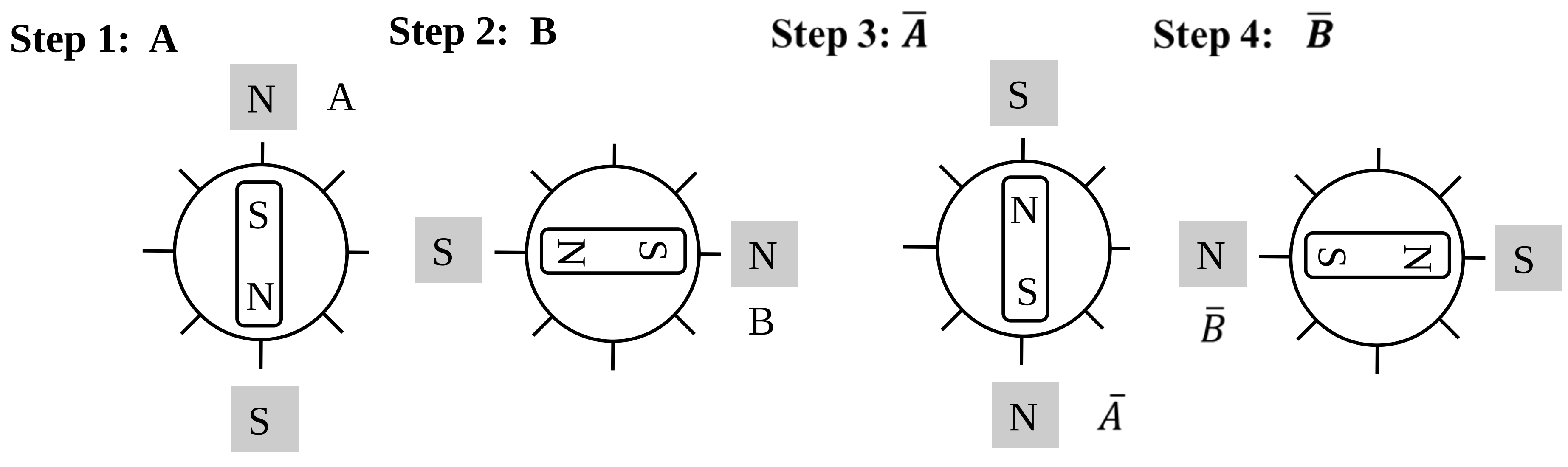


PM Stepper Motor Operation

- Stepper Motors can be actuated using four different methods:
  - Wave drive
  - Full stepping
  - Half-stepping
  - Microstepping
- Has to do with how phases are activated and in what combination
- Methods will be explained for two-phase motor
  - Can be generalized to motors with more phases

Wave Drive Actuation

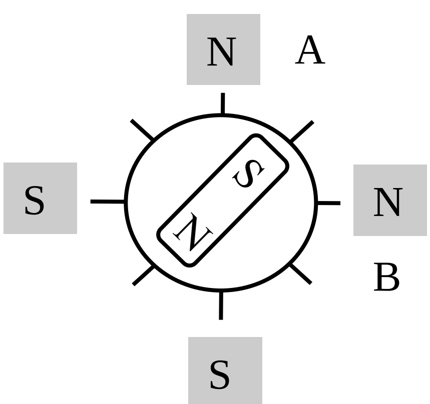
- Let two phases be denoted A and B
- Only one phase is active at each time (reduces torque)
- Phases are activated sequentially to turn motor in 90 deg increments
  - A = positive voltage across coils in phase A
  - $\bar{A}$ = negative voltage across coils in phase A



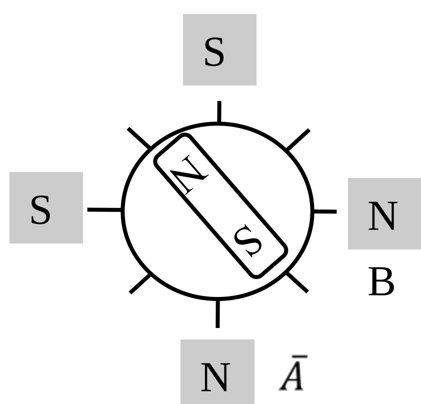
Full Stepping Actuation

- Two phases are always activated
  - Results in increased torque over wave drive method
- Phases again activated sequentially to turn motor in 90 deg increments
  - Now increments are offset 45 deg compared to wave drive method

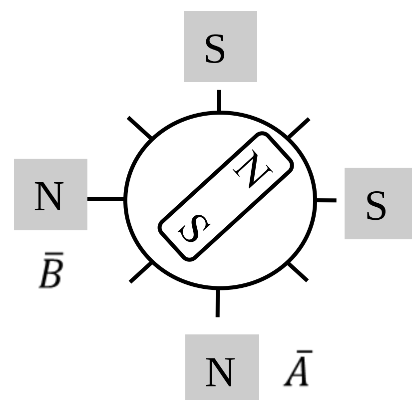
Step 1: AB



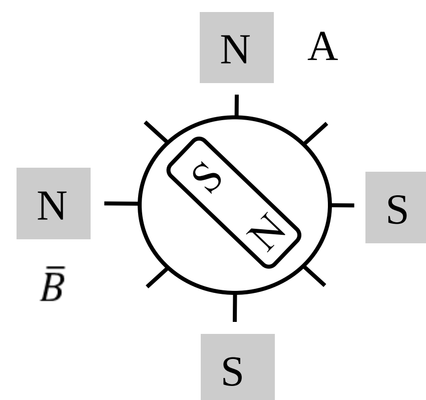
Step 2: $\bar{A}$B



Step 3: $\bar{A}\bar{B}$

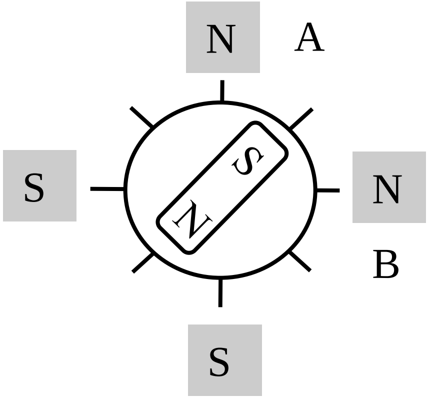


Step 4: A$\bar{B}$



Full Stepping Angle

- For 2-phase motor, step angle used in full stepping is 90 deg
- In general, full stepping angle of a PM stepper motor given by formula:



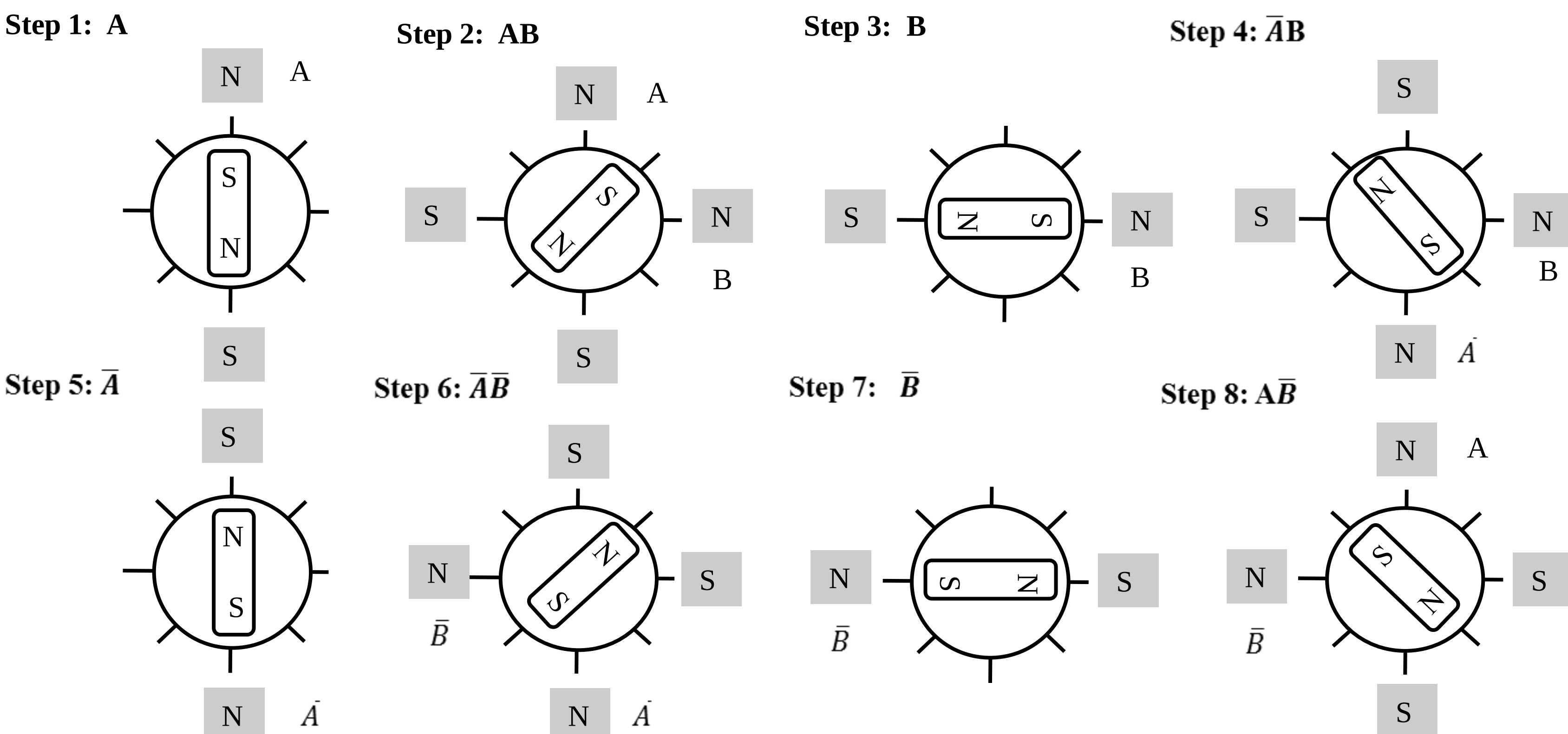
$$\Delta\theta = \frac{360^{\circ}}{2 \times P \times S}$$

P: Number of rotor pole pairs

S: Number of stator pole pairs

Half Stepping Actuation

- Method alternates between activating one phase and two phases at a time (yields 45 deg rotation)
  - Combines wave drive and full stepping actuation



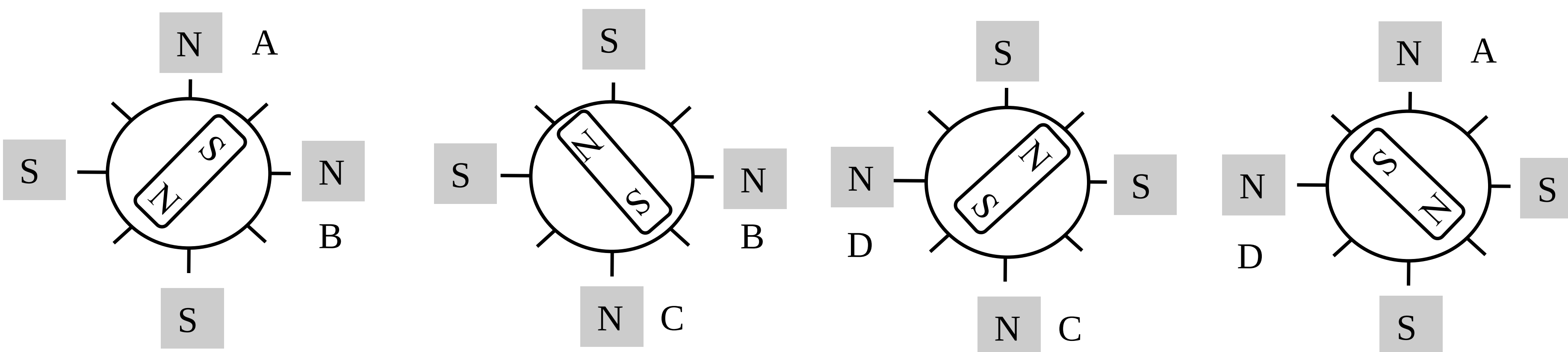
Unipolar vs Bipolar Motors

- In actuation methods described so far, voltage polarity across coils must be reversed in some steps
- This is called bipolar excitation
  - May be difficult to do in practice unless we have $+V_{dd}$ and $-V_{dd}$ available (or use H-bridge)
- Alternative is unipolar excitation
  - Only uses $+V_{dd}$, but requires use of four phase motor
  - Two opposing coils for each set of stator poles, wound in opposite direction
    - *These coils are only energized one at a time*

Unipolar Excitation

- Consider 4-phase stepper motor activated using full stepping method
  - Now coils are labeled *A*, *B*, *C*, *D*

Step 1: AB **Step 2: BC** **Step 3: CD** **Step 4: DA**



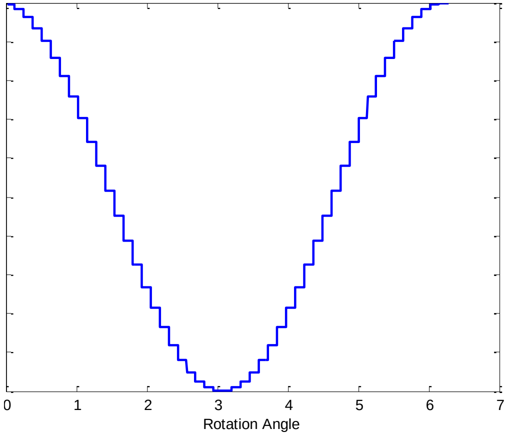
- *In bipolar excitation of 2-phase motor, we apply voltage in both directions across 2 phases*
- *Here we apply voltage in one direction only across 4 phases.*

Microstepping Actuation

- In above examples, we either turned coils on or off
- If we vary current in small steps, we can achieve very small step size of motor
  - Since this increases number of equilibrium positions of rotor
  - Can sometimes achieve about 1 deg increments
- Results in smoother motion, but torque decreases by 30-40% compared to full-stepping

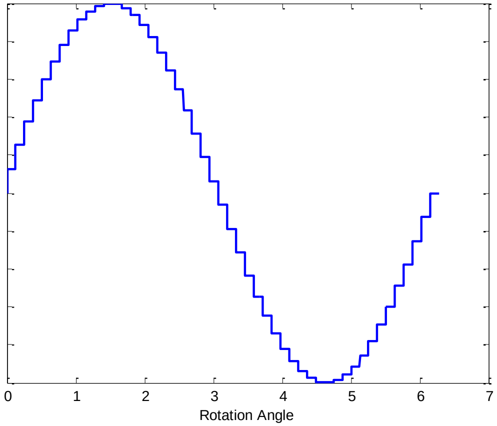
Current
(Phase A)

+
0
-



Current
(Phase B)

+
0
-



Hybrid Stepper Motors

- Hybrid stepper motors have more complex construction than PM stepper motors
  - They can achieve much smaller rotation increments without using microstepping

- Rotor has permanent magnet mounted <u>axially</u> so that one end polarized north and other end polarized south
- Rotor and stator have “teeth” that align in various configurations during rotation

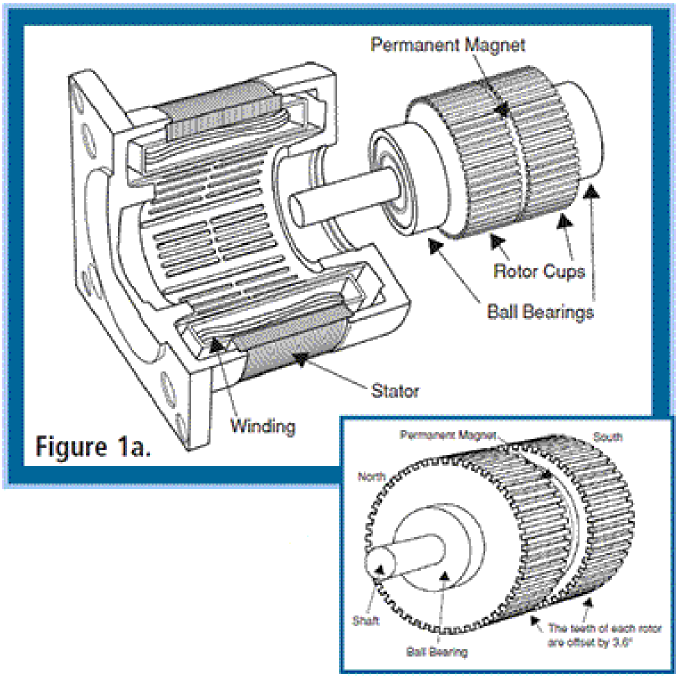
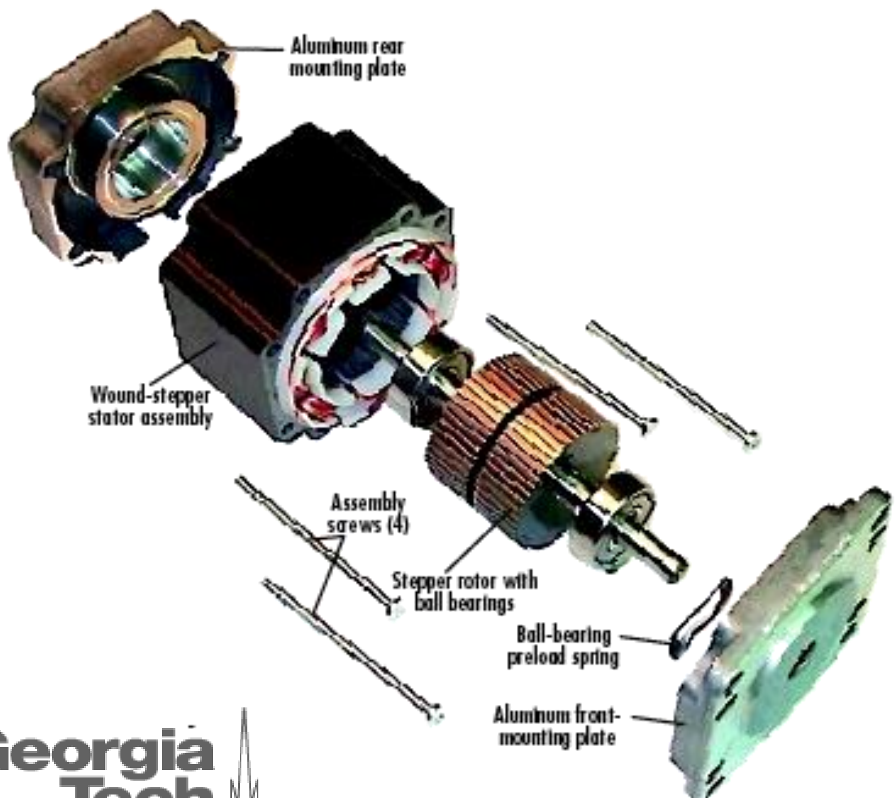


Figure 1a.

Hybrid Stepper Motors

- Permanent magnet in rotor is surrounded by "cups" containing teeth



- Consider case of 1.8 deg hybrid stepper motor (most common)
- Each cup contains 50 teeth at 7.2 deg increments
- Teeth of top cup offset from teeth of bottom cup by 3.6 deg
- Stator contains two phases (two sets of wound coils) in bipolar configuration

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Hybrid Stepper Motors

- When Phase Acc is energized, coils at 12 and 6 o'clock are N and attract magnetically S end of rotor
- Coils at 3 and 9 o'clock attract magnetically N end of rotor
- Because spacing of teeth on stator and rotor are different, there is offset between teeth and next Phase B
- Energizing Phase Bcc next will cause rotor to turn 1/4 tooth distance, which is 7.2 deg / 4 = 1.8 deg

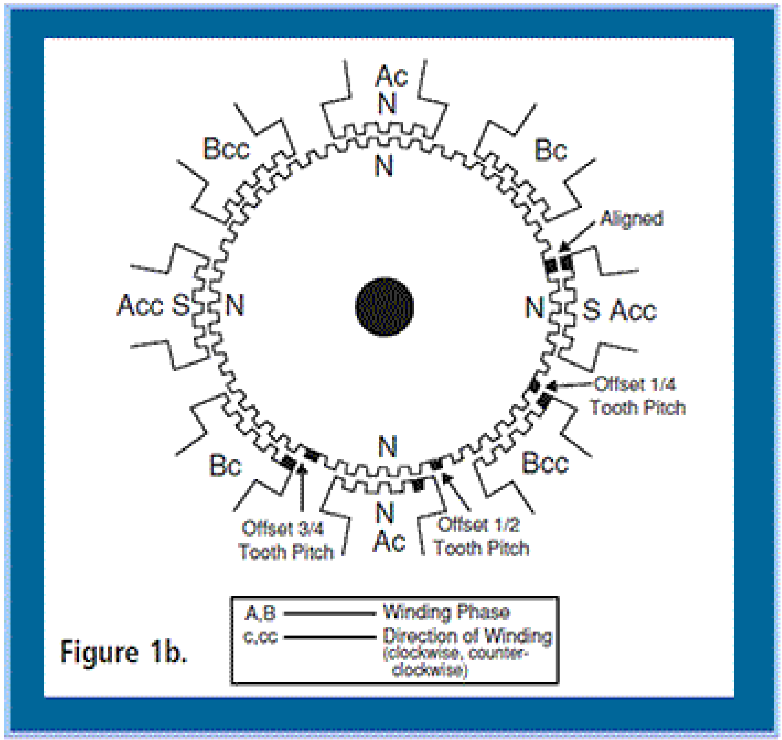


Figure 1b.

Hybrid Stepper Motors

- Motor controller can thus rotate rotor clockwise in 1.8 deg increments by activating phases in following order: Acc, Bcc, Ac, Bc, etc.
- Counterclockwise rotation achieved by activating phases in opposite order
- Hybrid motors tend to be more expensive than PM steppers, used in industrial applications where higher precision is needed
- What is benefit of using hybrid motor rather than microstepping of PM motor?

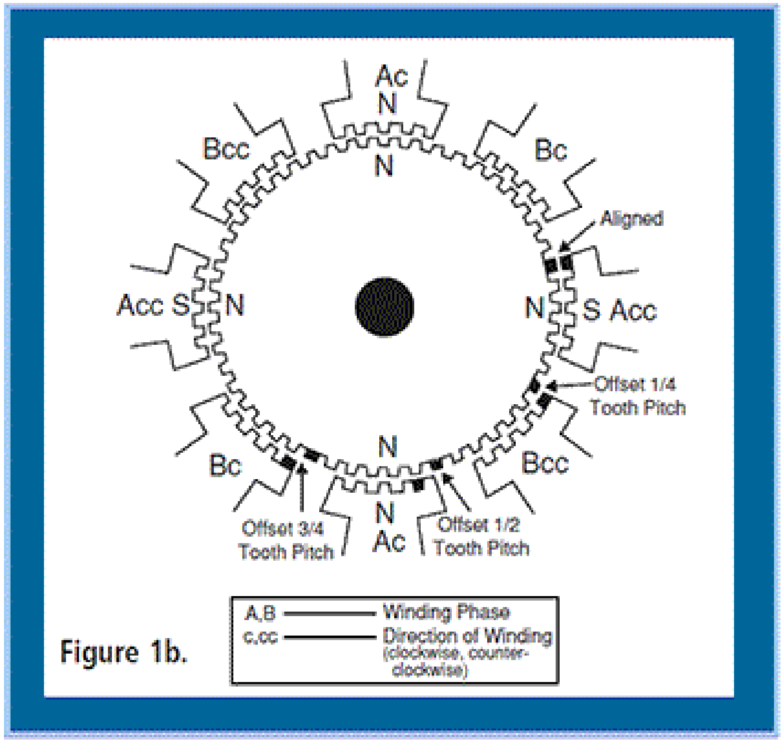
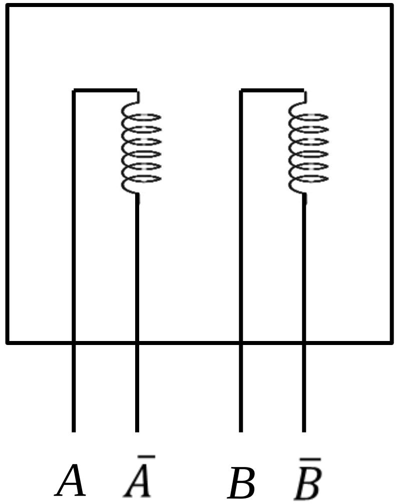


Figure 1b.

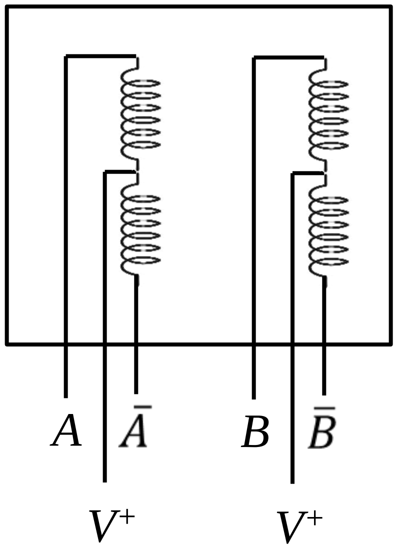
Stepper Motor Wiring

- Most stepper motors come with either 4, 6, or 8 leads
  - 4 lead configuration: Used only with bipolar excitation
  - 6 lead configuration: Used for unipolar (4-phase) or bipolar excitation

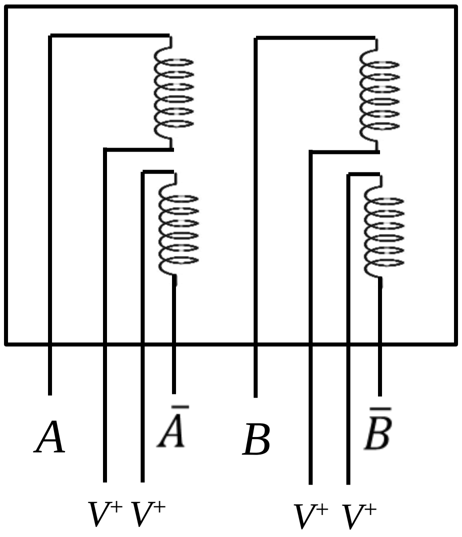
4 Lead Configuration



6 Lead Configuration

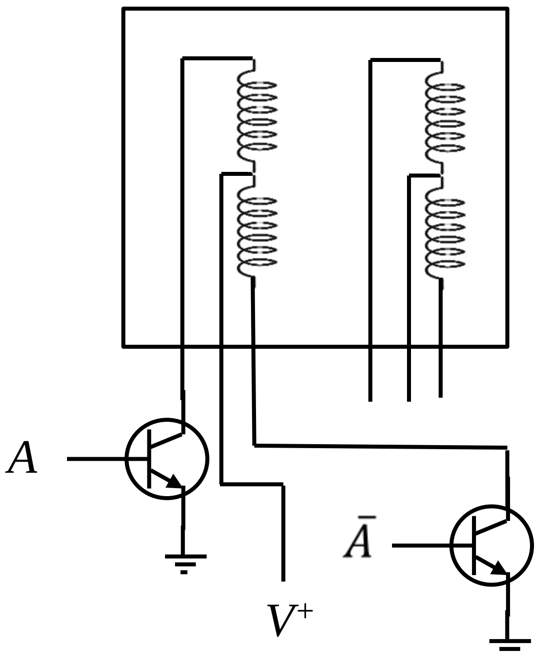


8 Lead Configuration



Stepper Motor Drivers

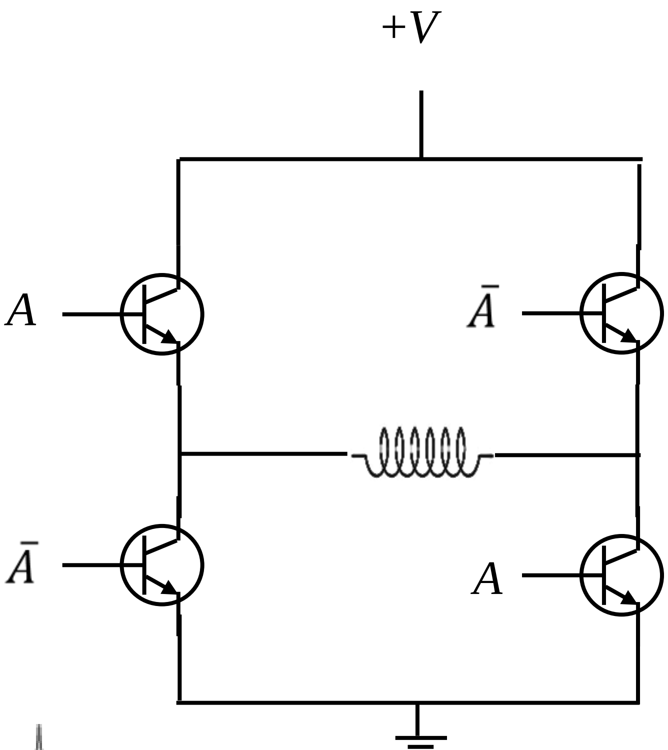
- Stepper motor drivers can be constructed in various ways
- Simple unipolar stepper motor driver can be constructed using two transistors



- Transistor used for each coil winding for unipolar excitation
- One transistor activated at a time (sequentially)
- Same transistor configuration used for phase $B/\bar{B}$

Stepper Motor Drivers

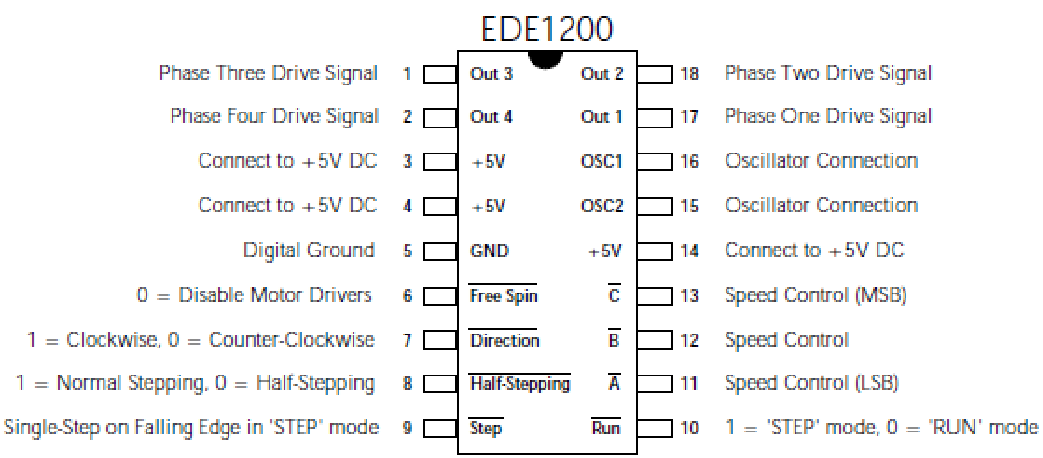
- Simple bipolar stepper motor driver can be constructed using H-bridge

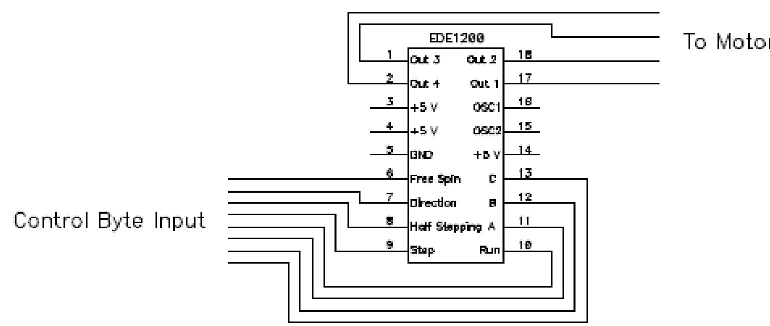


- H-bridge inputs used to activate each phase in sequence
- Interface transistor gates to MCU pins
- Would also need similar H-bridge arrangement for phases $B/\bar{B}$ in 2-phase motor

Stepper Motor Drivers

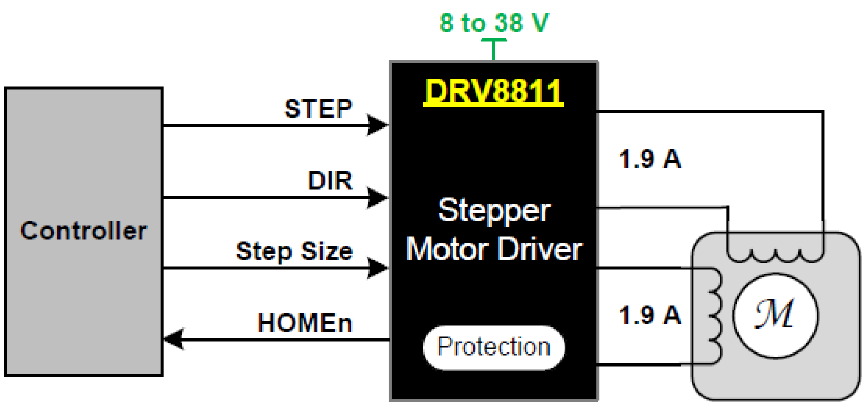
- Various IC’s available to interface stepper motor with MCU
- Example: Paladin Semiconductor PDN1200
  - Unipolar driver capable of full-step or half-step actuation

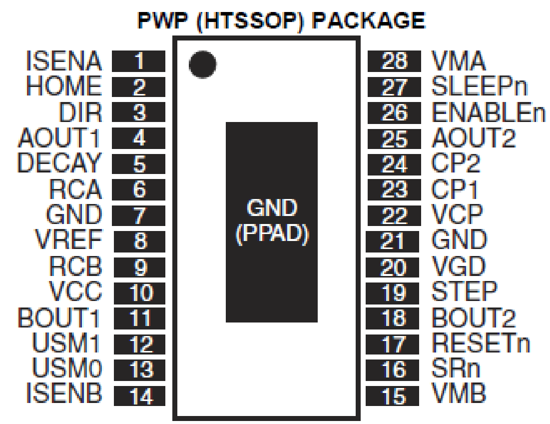


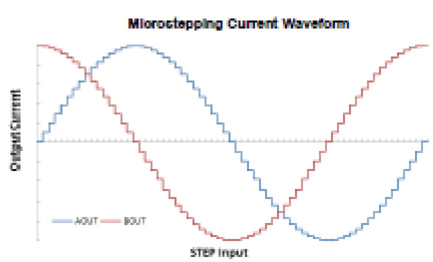


Stepper Motor Drivers

- Example: TI DRV8811 microstepping motor driver
  - Capable of automatically performing microstepping – provides a step size input



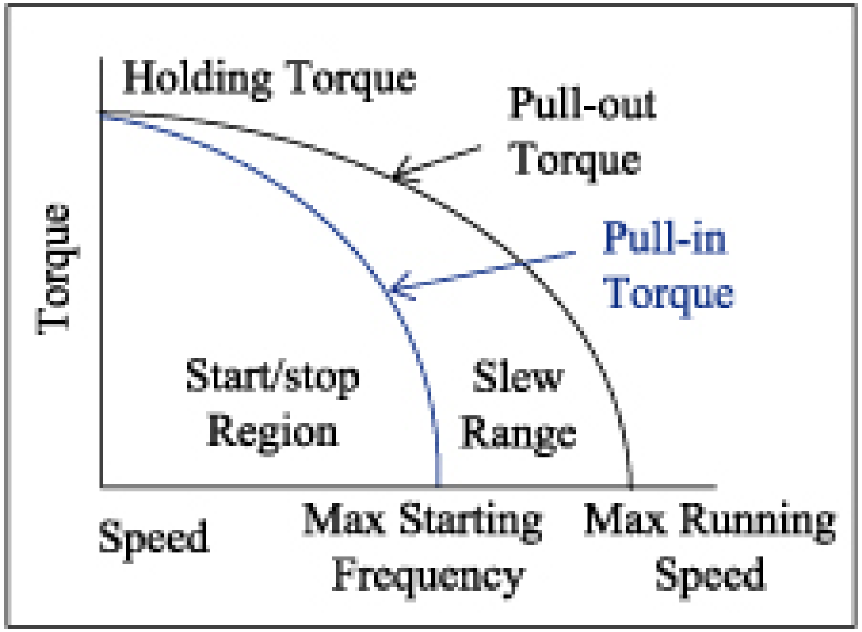




Stepper Motor Specifications

- Speed-torque curve has two regions of operation
  - Speed usually defined in pulses per second or Hz

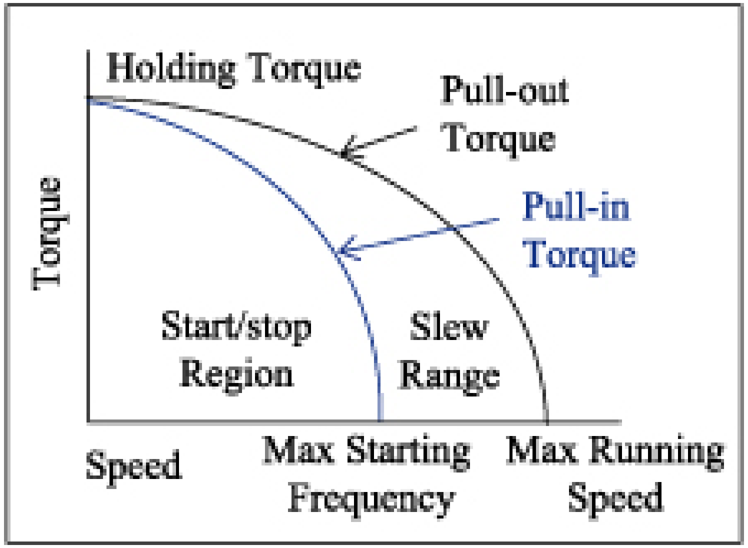
- Start-stop region – motor can start, stop, and change direction instantly without losing any steps
- Slewing region – motor may skip steps if commanded to instantly start, stop, or reverse (Why is this bad?)
- Motor must gradually accelerate into slewing region from start-stop region



Stepper Motor Specifications

- Specifications defined in terms of holding torque, pull-out torque curve, pull-in torque curve, max running speed, and max starting speed

- Holding torque is max torque that can be applied to a powered but not rotating motor without it moving from its rest position
- Manufacturers usually provide pull-out torque curve
- These curves are function of both motor and driver used to actuate motor phases



Example Stepper Motor Datasheet

- Portescap 35L048B 2-Phase Stepper Motor

Electrical Data	35L048B1U Unipolar	35L048B2U Unipolar	35L048B1B Bipolar	35L048B2B Bipolar	
1 Operating Voltage	5	12	5	12	VDC
2 Resistance per Phase, ± 10%	11.0	64.0	11.0	64.0	Ohms
3 Inductance per Phase, typ	7.8	40.0	15.0	72.0	mH
4 Rated Current per Phase *	0.45	0.19	0.45	0.19	A
Coil independent parameters					
5 Holding Torque, MIN *	25 (3.5)	25 (3.5)	28 (4)	28 (4)	mNm (oz-in)
6 Detent Torque, Max	4.2 (0.6)	4.2 (0.6)	4.2 (0.6)	4.2 (0.6)	mNm (oz-in)
7 Rotor inertia	4 (0.021)	4 (0.021)	4 (0.021)	4 (0.021)	(gcm^2) (oz-in-s^2)
8 Step Angle	7.5	7.5	7.5	7.5	Degree
9 Absolute accuracy 2 ph. On, Full step	± .5	± .5	± .5	± .5	Degree
10 Steps per Revolution	48	48	48	48	
11 Ambient Temp Range (operating)	-20 to +70 (-4 to +158)	-20 to +70 (-4 to +158)	-20 to +70 (-4 to +158)	-20 to +70 (-4 to +158)	°C (°F)
12 Maximum Coil Temperature	130 (266)	130 (266)	130 (266)	130 (266)	°C (°F)
13 Bearing Type	Sintered Bronze Sleeve	Sintered Bronze Sleeve	Sintered Bronze Sleeve	Sintered Bronze Sleeve	
14 Insulation Resistance at 500 VDC	100	100	100	100	Mohms
15 Dielectric Withstanding Voltage	650 for 2 seconds	650 for 2 seconds	650 for 2 seconds	650 for 2 seconds	VAC
16 Weight	88 (3.1)	88 (3.1)	88 (3.1)	88 (3.1)	g (oz)
17 Leadwire	AWG 26, UL 1430	AWG 26, UL 1430	AWG 26, UL 1430	AWG 26, UL 1430	

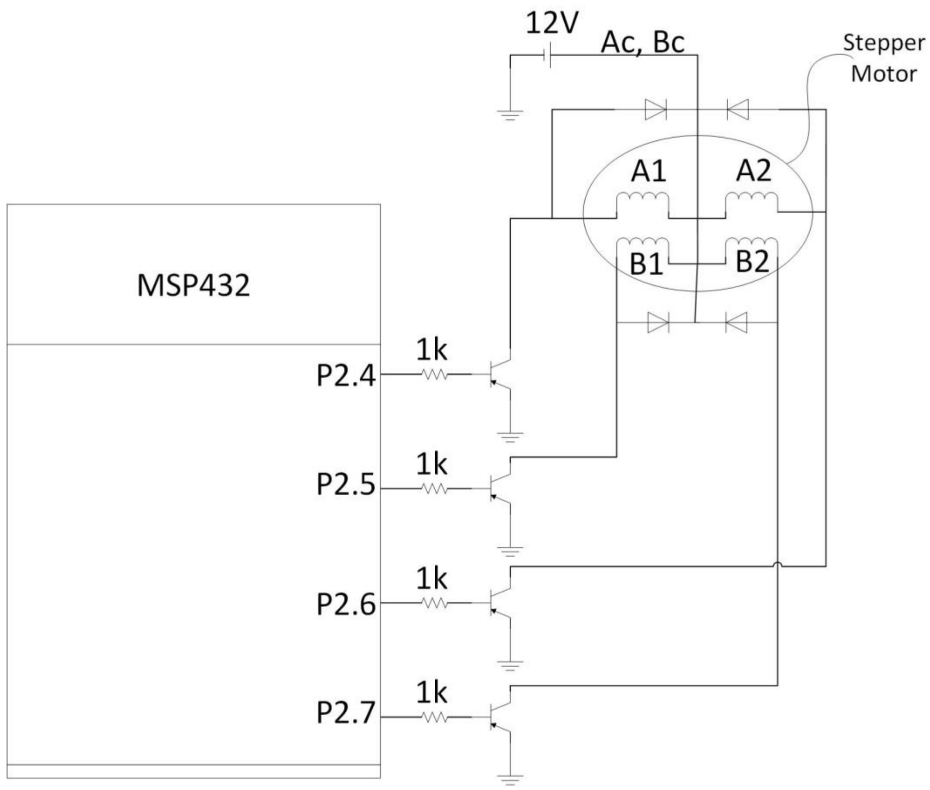
All Motor Data Values at 20°C Unless Otherwise Specified

* Energize at Rated Current, 2 Phase On

Interfacing with the MSP432

- Let’s look at a schematic of how we would interface an MCU to a 2-phase stepper motor for unipolar actuation

- Each phase connected to one output pin on microcontroller
- Rotation achieved by setting one output pin high (all others low) in a specific sequence



Example Program: Stepper Motor Control

- Let's look at an example MSP432 code that rotates a stepper motor using unipolar excitation
  - Circuit on previous page

Actuator Comparisons for Mechatronics Systems

Characteristic	Brushed DC	Brushless DC	Stepper
Supply Voltage	Needs simple DC voltage power source	Uses DC voltage but needs special amplifier	Uses DC voltage but requires special amplifier to drive each phase
Direction Change	Done by reversing polarity to motor leads or with H-bridge	By activating phases in the reverse manner	By activating phases in reverse manner (or switching direction signal if stepper motor driver is used)
Speed Change	Done by changing value of input voltage	Done by changing rate of activating phases	Done by changing rate of activating phases (or by changing pulse rate if stepper motor driver is used)
Maintenance	Need to periodically replace brushes and resurface commutator	No wear problems due to absence of brush contact – low maintenance	No wear problems due to absence of brush contact – low maintenance
Available Sizes	Few watts to several Hp (1 Hp = 746 W)	Few watts to few hundred Hp	No Hp rating since they do not run continuously. Max torque rating up to tens of ft-lbs