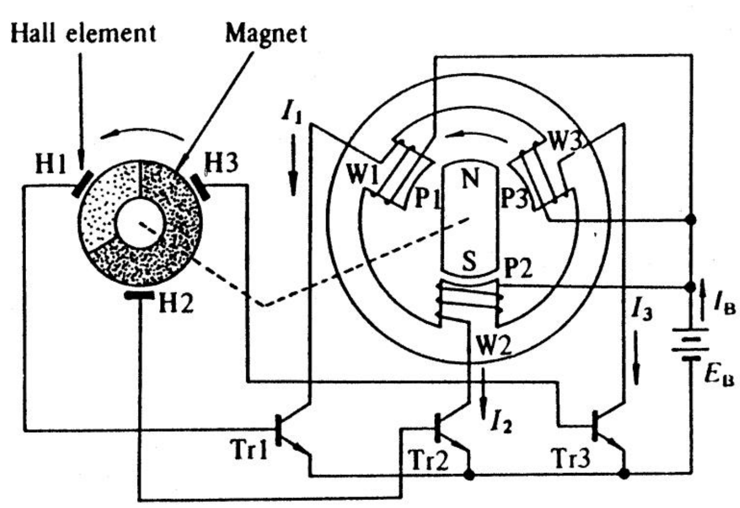
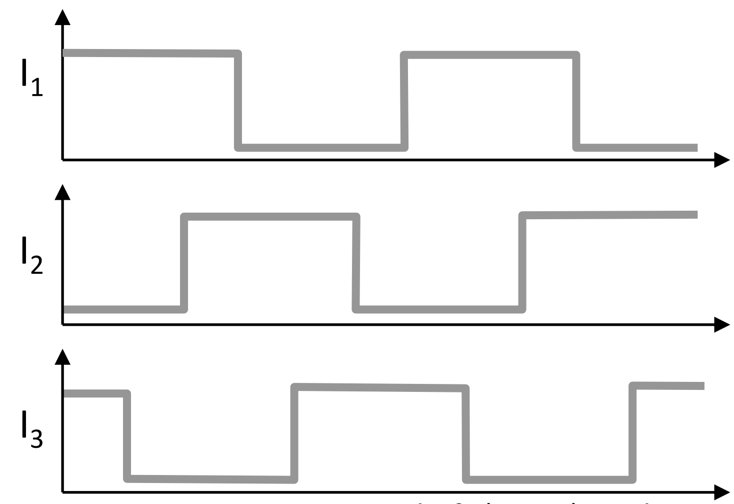
UNIT 10:
STEPPER MOTORS

BRUSHLESS DC (BLDC) MOTORS

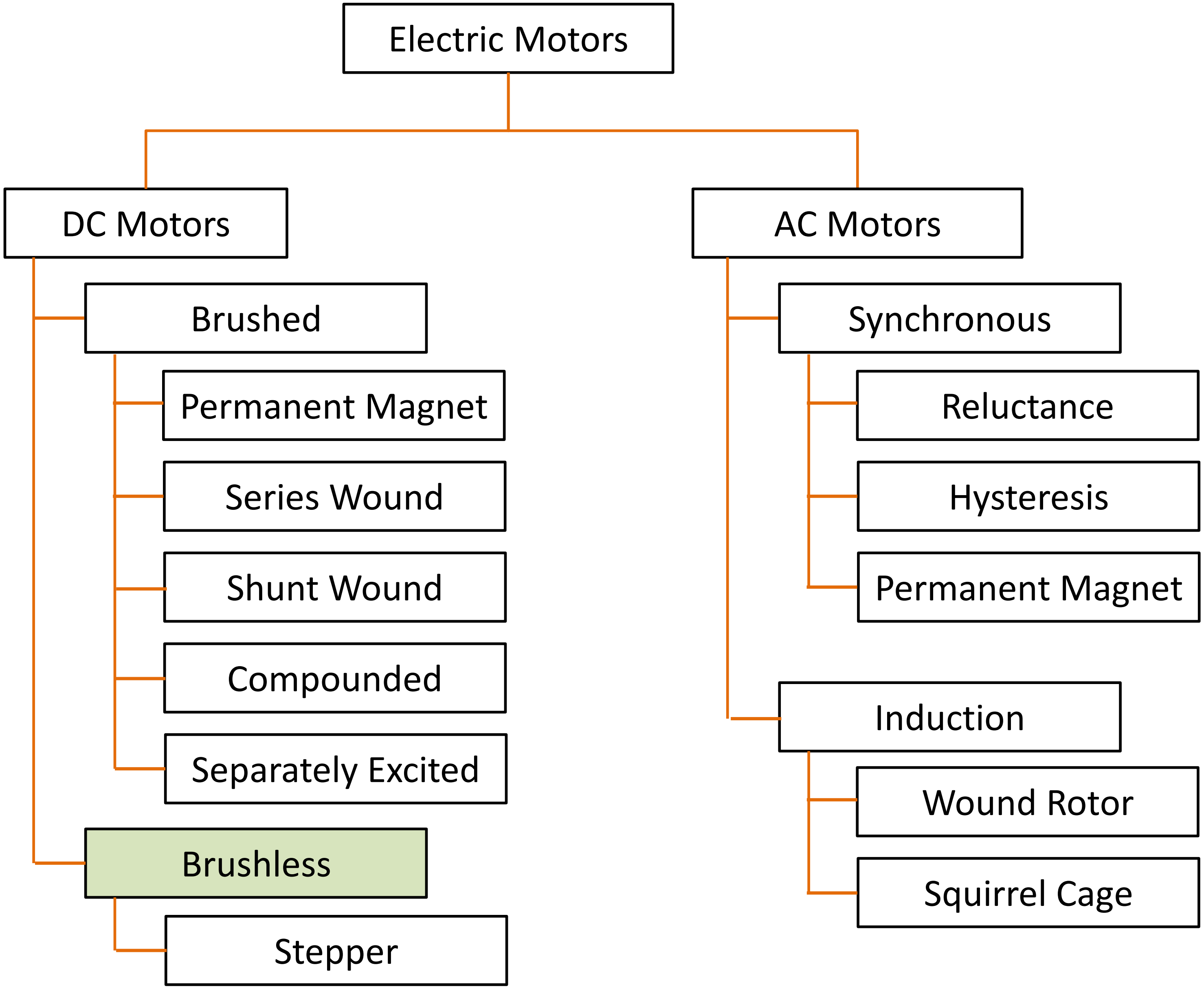
Permanent magnet on rotor (usually the outer case) and three phase coil excitation on stator. In this case, the stator is the armature, as it is the component through which current flows.

Use rotor angular position feedback to electronically commutate the coil (phase) currents.





ELECTRIC MOTORS



BRUSHLESS DC (BLDC) MOTORS

Image: http://electronics.howstuffworks.com/brushless-motor.htm

BRUSHLESS DC (BLDC) MOTORS

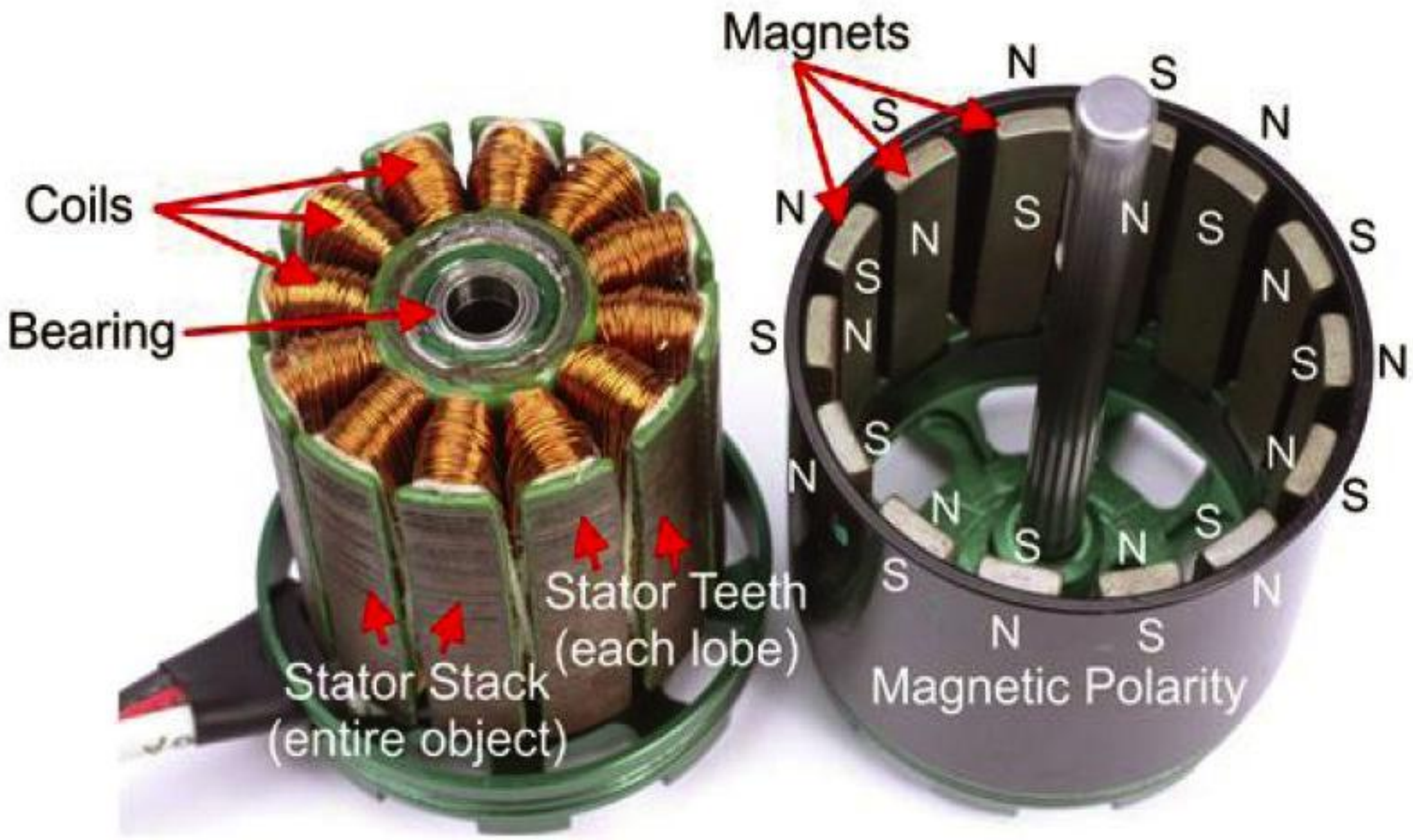
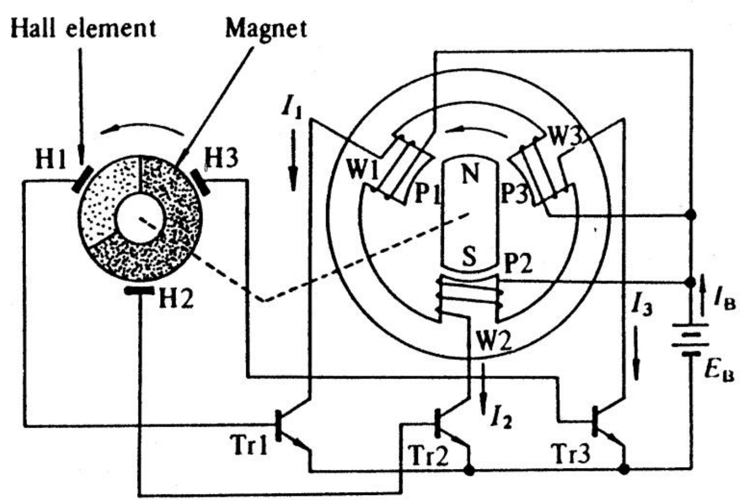
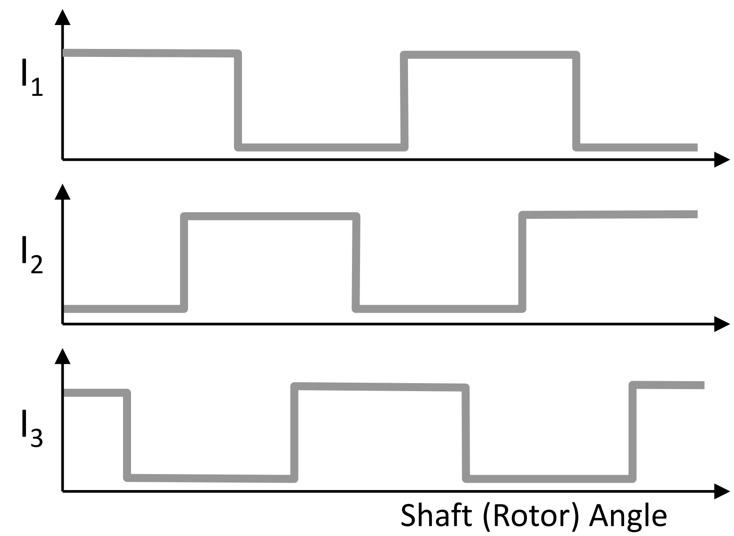


Image: http://www.rcuniverse.com/magazine/reviews/1344/BrushlessMotors7.jpg

BRUSHLESS DC (BLDC) MOTORS

- Uses three-phase DC signals and requires three channels of power amplification.
- Excitation is a function of rotor position. On-off excitation switching needs discrete point measurement.
  - Hall effect sensors are generally used.
  - Non-excited coil back-emf can also be used.

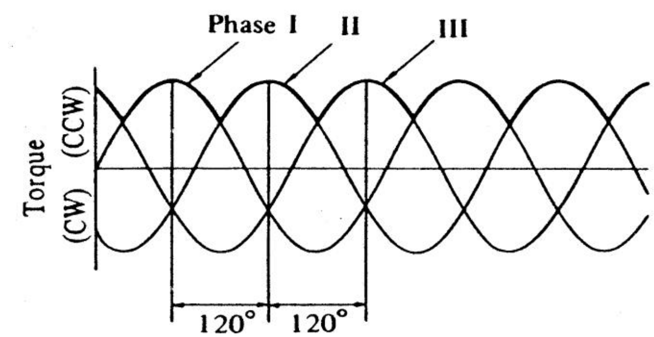




BRUSHLESS DC (BLDC) MOTORS

Pros

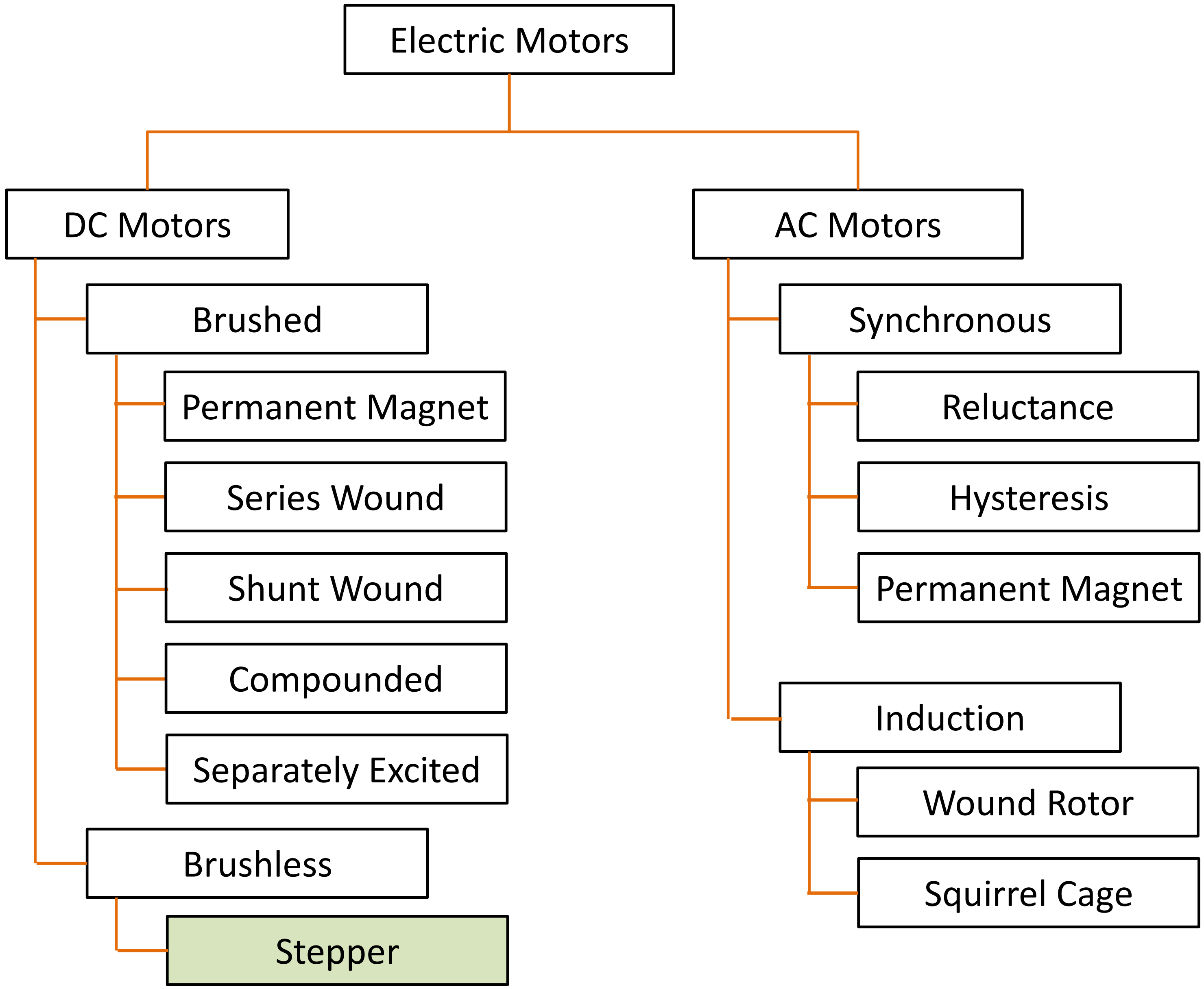
- No Brushes
  - Less maintenance
  - Less electrical noise
  - Can use higher voltages
  - More efficient, due to friction reduction



Cons

- Require Additional Components
  - More electronics
  - Rotor position sensor
- Higher Torque Ripple
  - Can be reduced by using sinusoidal excitation
    - Requires linear or PWM amplifier with higher precision rotor position measurement.
  - Can be reduced by adding more commutation points
    - Not practical – needs too much more electronics.

STEPPER MOTORS



STEPPER MOTORS

What does it all mean?

Stepper Motor: Bipolar, 200 Steps/Rev, 20×30mm, 3.9V, 0.6 A/Phase

This small NEMA 8-size hybrid bipolar stepping motor has a 1.8° step angle (200 steps/revolution). Each phase draws 600 mA at 3.9 V, allowing for a holding torque of 180 g-cm (2.5 oz-in). With a weight of 60 g, this is one of the smallest stepper motors we carry.

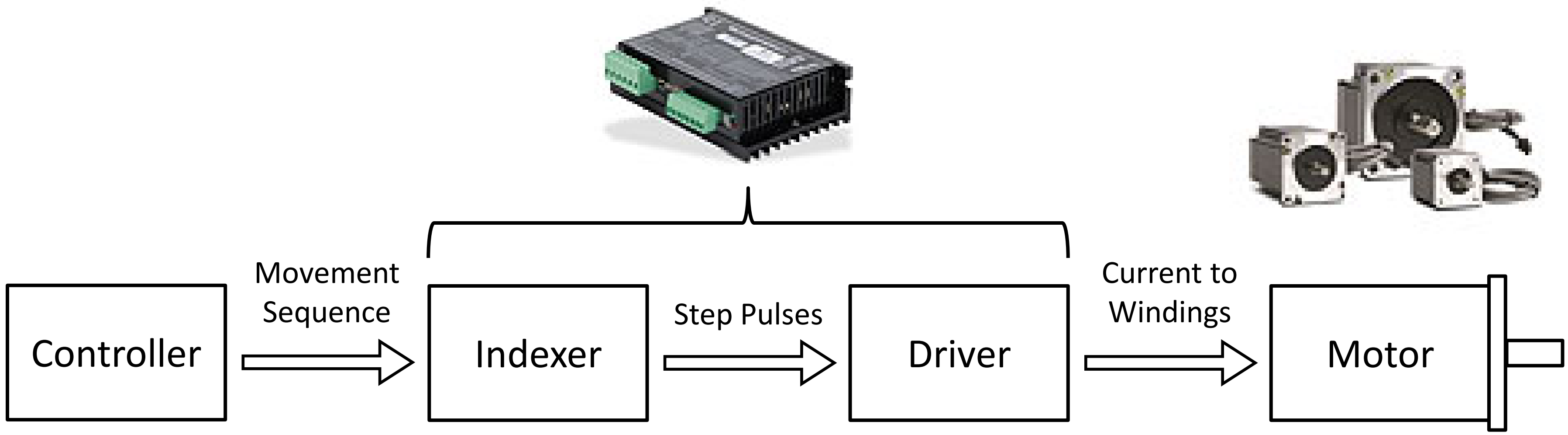
Image: http://www.pololu.com/category/87/stepper-motors

STEPPER MOTORS

- Stepper motors convert digital pulses to discrete mechanical movement.
- The output shaft rotates in distinct angular increments (steps) as current is selectively routed through the stator windings in response to applied digital sequences.

Image: http://www.engineersgarage.com/articles/stepper-motors

STEPPER MOTORS



Images: http://www.automationdirect.com/adc/Overview/Catalog/Motion_Control/Stepper_Systems

STEPPER MOTORS

Advantages:

- Simplicity in construction
- Position control without feedback component
- No brushes, no contacts
- Low maintenance

Disadvantages:

- Resonance effect and long settling time
- Heat (consume current regardless of load condition)
- Slower than servo (DC) systems
- Variable holding torque (cogging)

STEPPER MOTORS

Three types:

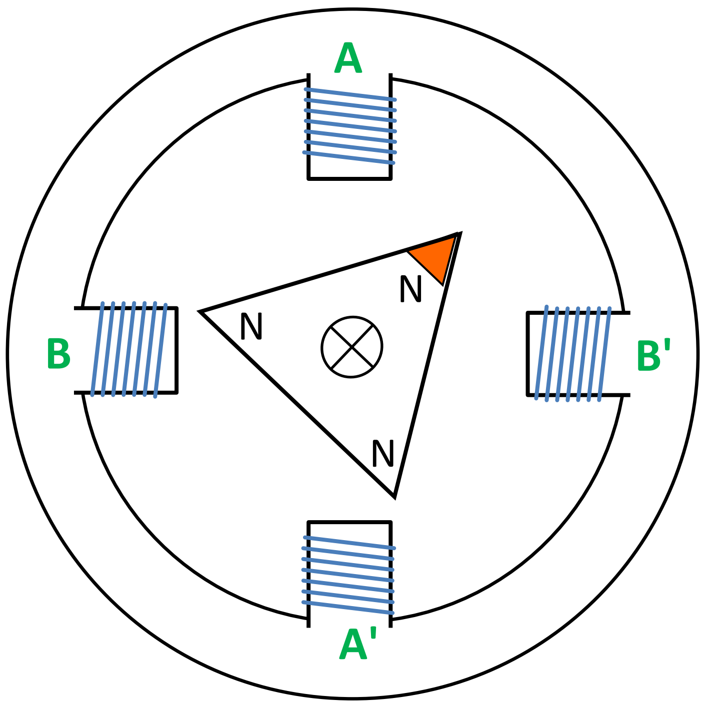
- Permanent Magnet (PM)
- Variable Reluctance (VR)
- Hybrid

PERMANENT MAGNET (PM) STEPPER

Permanent magnets are attached to rotor. These magnets are attracted to magnetic poles of the opposite polarity.

Windings allow magnetic field polarities to be selectively established around periphery of stator interior.

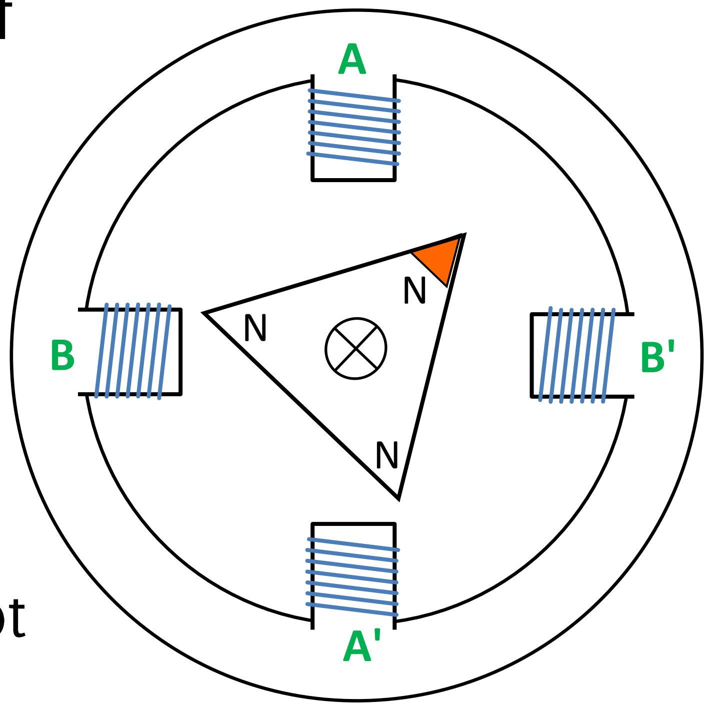
Two stator windings are required to establish a phase. The example shown has two phases, represented by A-A' and B-B'



PERMANENT MAGNET (PM) STEPPER

Equilibrium position depends on phase of excitation.

- Rotor and stator each have their own magnetic fields.
- Misalignment between stator and rotor magnetic poles causes torque, which aligns rotor with stator.
- If excitation is held constant, rotor will not move.
- If external torque is applied to rotor, it moves. As rotor moves, field misalignment again generates a restoring torque. This effect acts like a (nonlinear) spring.

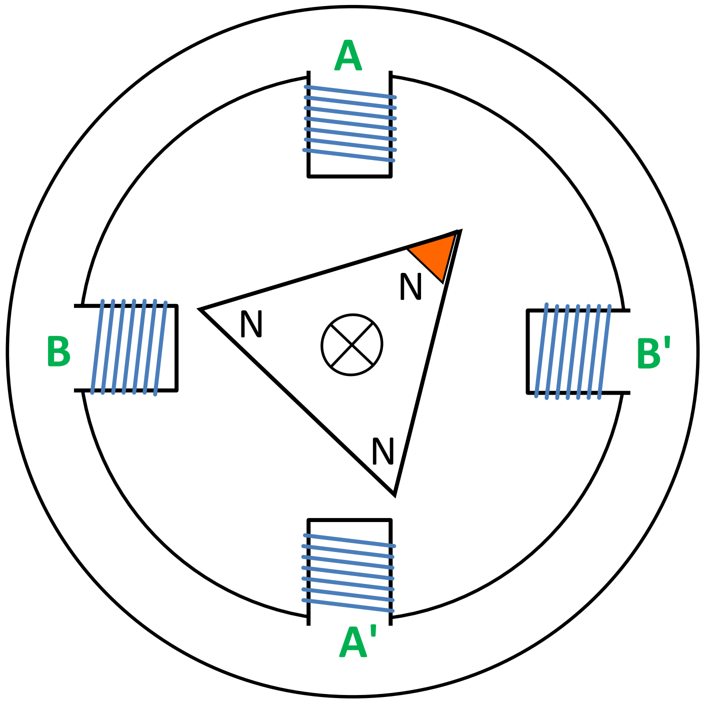


PERMANENT MAGNET (PM) STEPPER

The magnetic field will generate holding torque even if the field coils are not excited – *detent torque.*

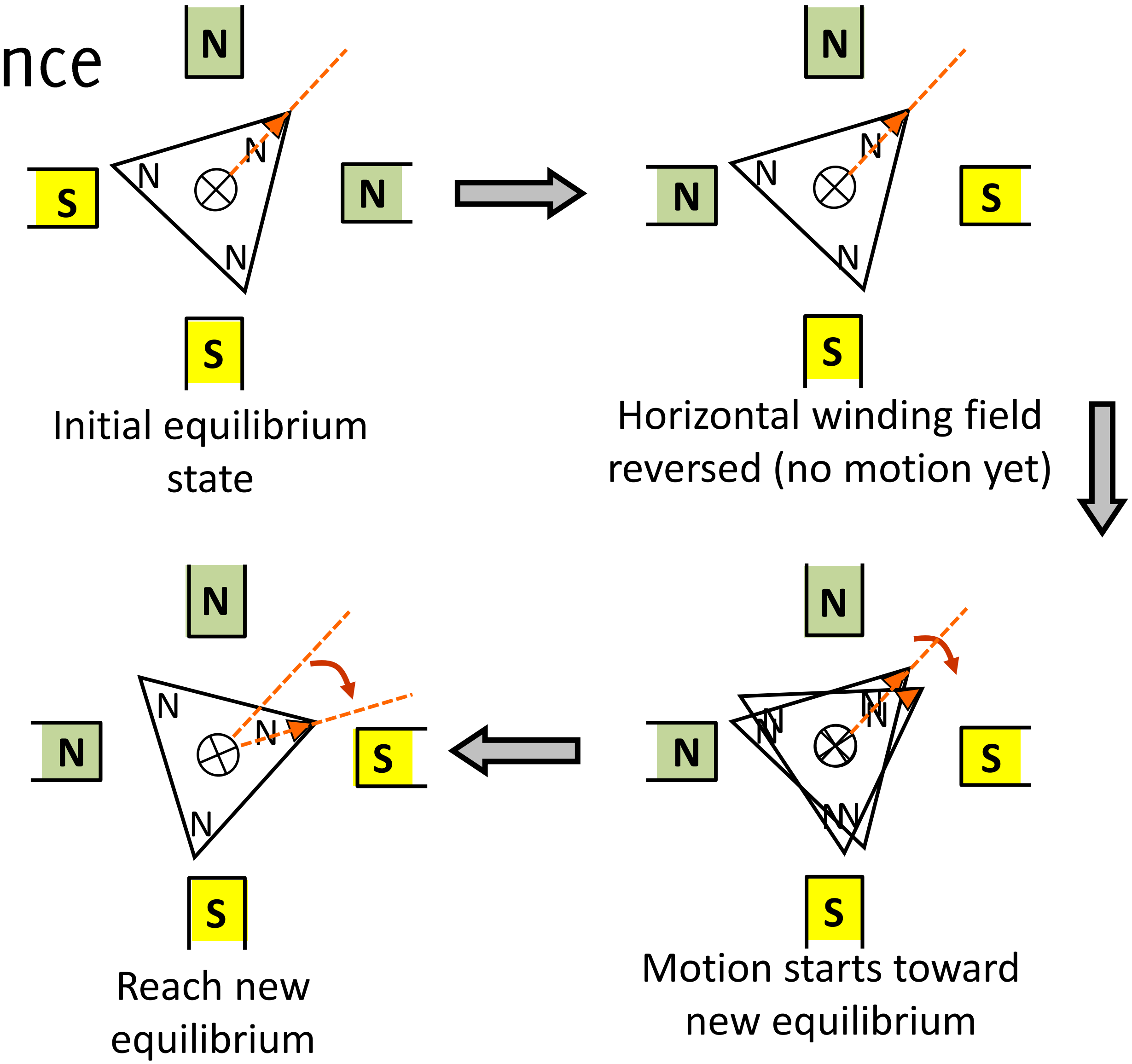
Full holding torque is available at standstill when field coils *are* energized.

Increasing the number of poles reduces the step size. Typical step angles from 7.5 to 45 degrees.



PERMANENT MAGNET (PM) STEPPER

Stepping Sequence

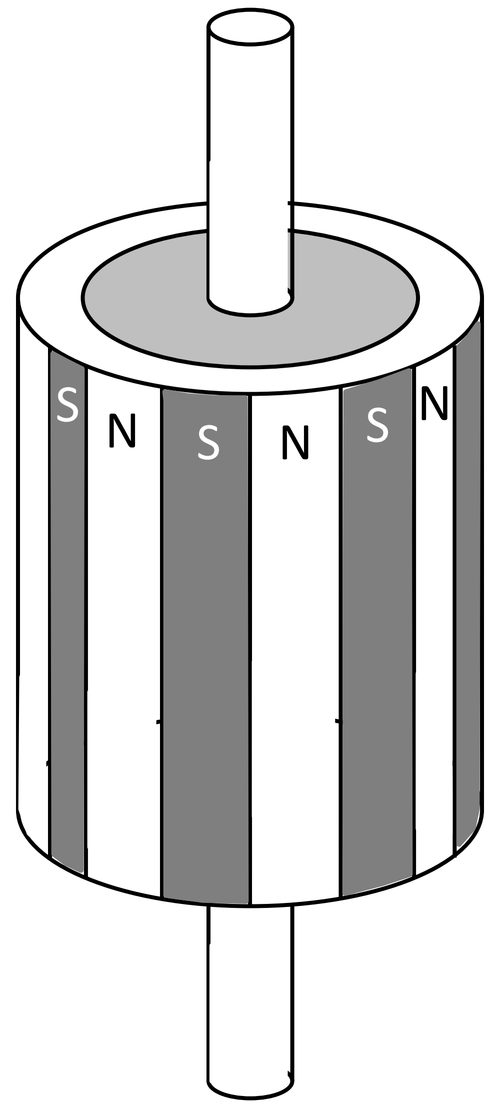


PERMANENT MAGNET (PM) STEPPER

No teeth on a PM stepper rotor

Use of rare earth magnets can increase magnetic flux and, hence, torque levels.

How else might we modify magnetic flux?

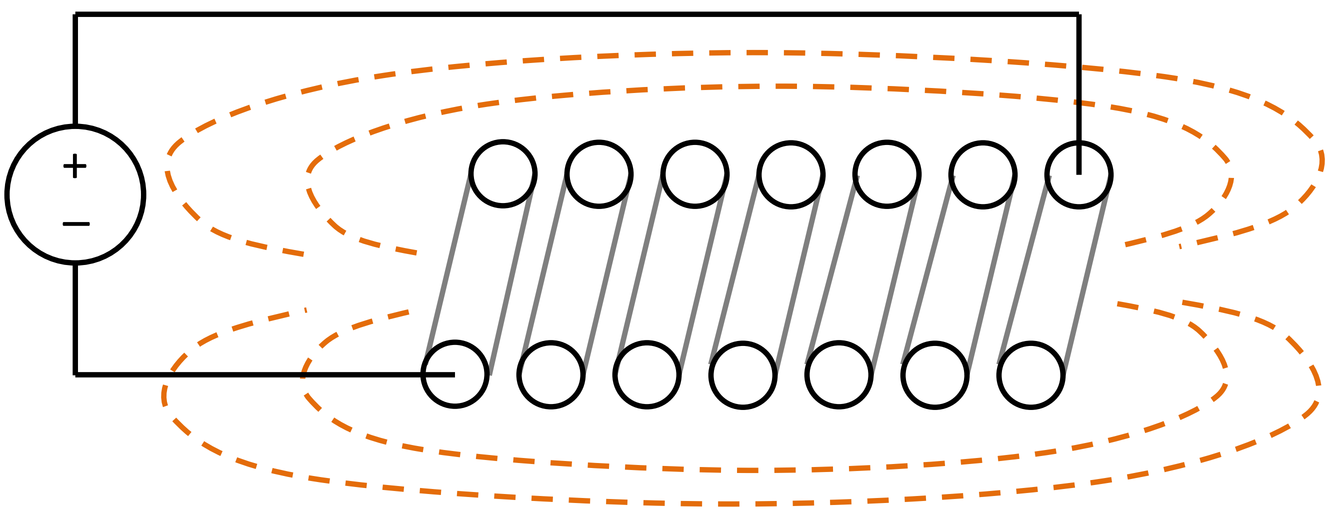


MAGNETIC FIELD AND FLUX

In an electromagnet, electric current passing through a winding produces a magneto-motive force (analogous to electrical voltage) equal to the product of winding turns and current:

$$\mathcal{F} = Ni$$

Units of $\mathcal{F}$ are amperes (A) or ampere turns (A-t).



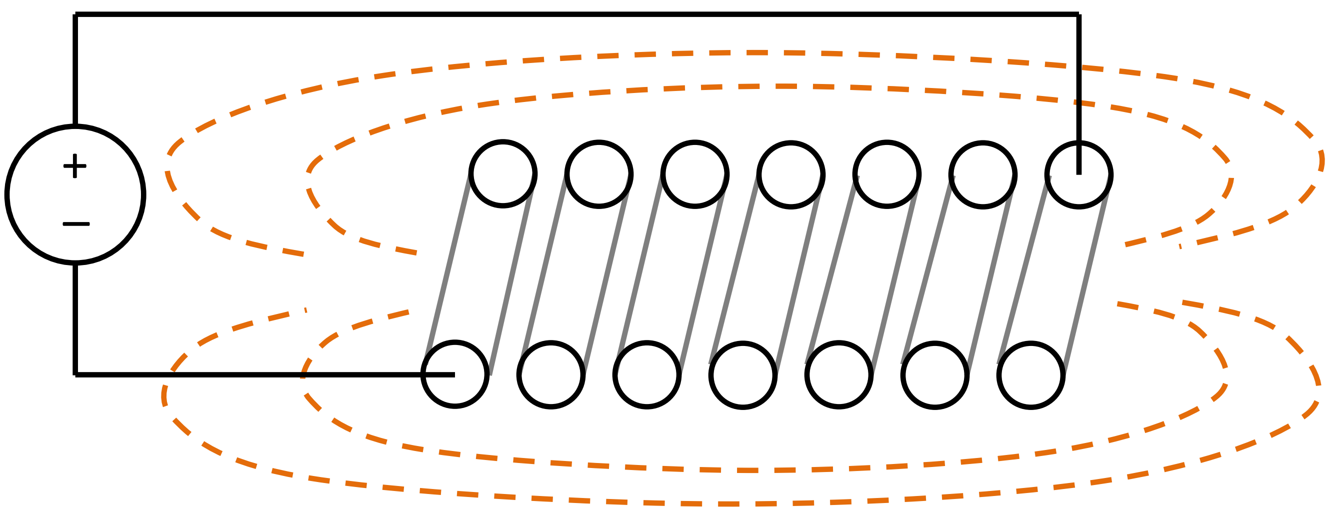
MAGNETIC FIELD AND FLUX

Magneto-motive force is also equal to the product of magnetic flux and reluctance (magnetic resistance):

$$\mathcal{F} = \Phi\,\Re_m$$

Note the similarity to Ohm's law:

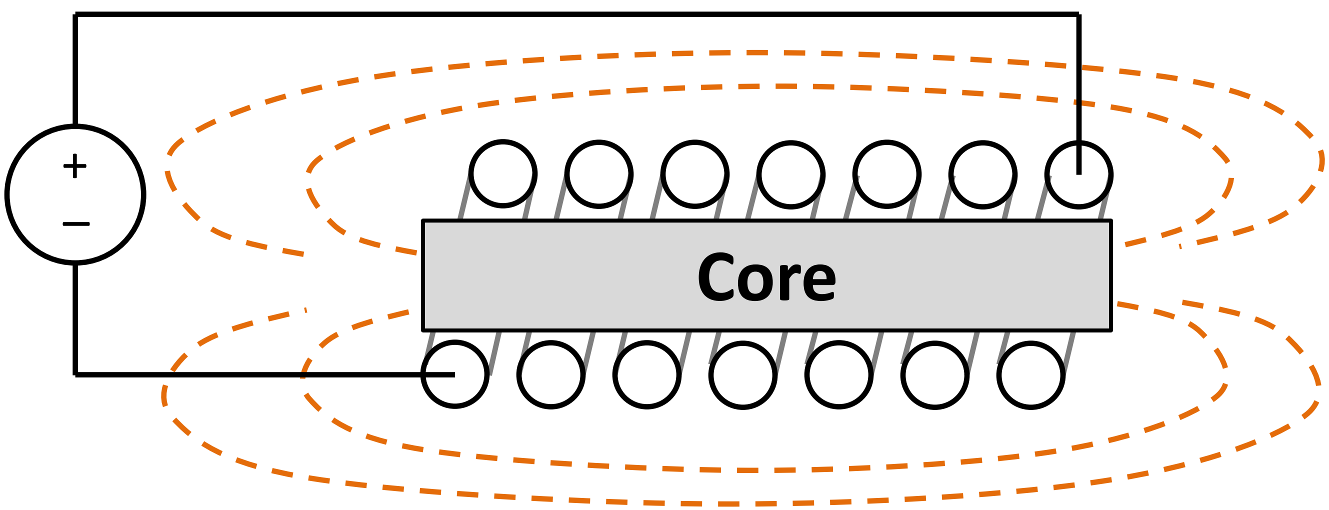
$$V = i\,R$$



MAGNETIC FIELD AND FLUX

Inserting a ferromagnetic core lowers the reluctance, and thereby increases the magnetic flux through the interior of the winding:

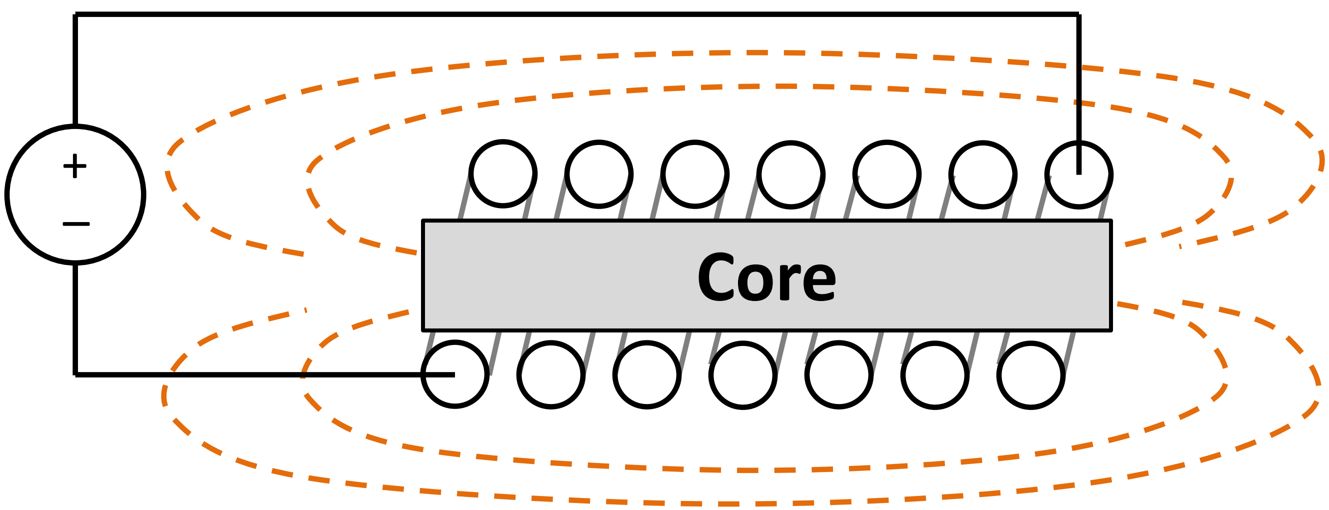
$$\mathcal{F} = \Phi \, \Re_m$$



MAGNETIC FIELD AND FLUX

Thus, there are three ways to modify the magnetic flux (Φ) when passing current through a motor winding:

- Increase number of winding turns
- Increase current flowing through winding
- Change magnetic resistance (reluctance, $\Re_m$) of core

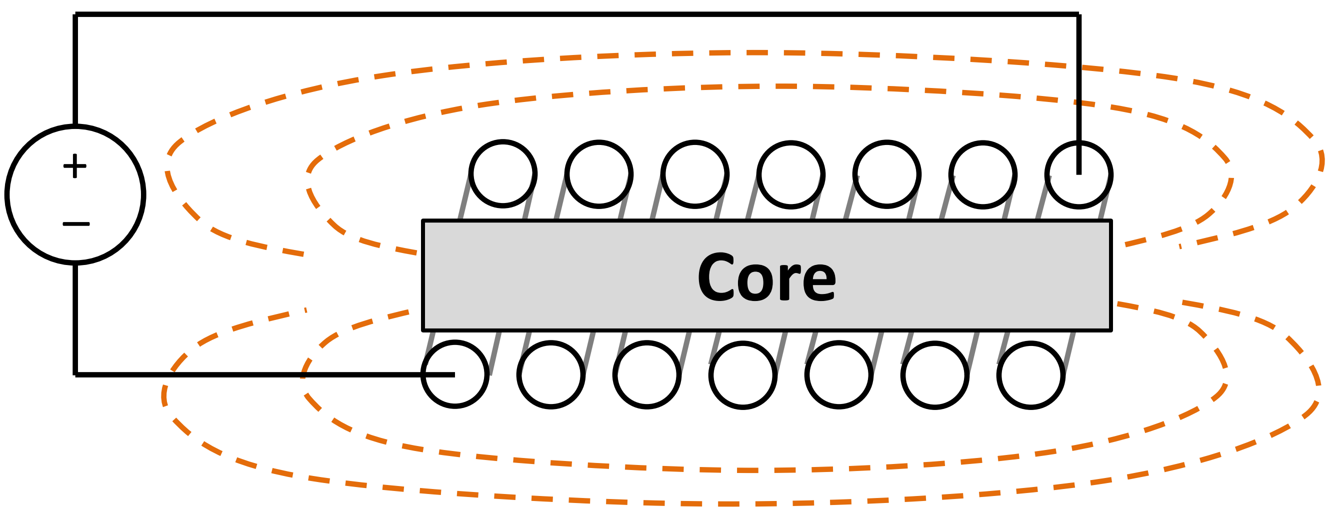


$$\Phi = \frac{NI}{\Re_m}$$

MAGNETIC FIELD AND FLUX

In the same way that electrical current follows the path of least resistance, magnetic flux follows the path of least magnetic reluctance.

We use teeth on rotor body to modulate magnetic reluctance.

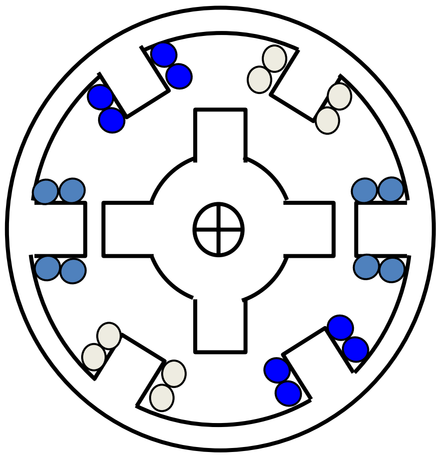


$$\Phi = \frac{NI}{\mathfrak{R}_m}$$

VARIABLE RELUCTANCE (VR) STEPPER

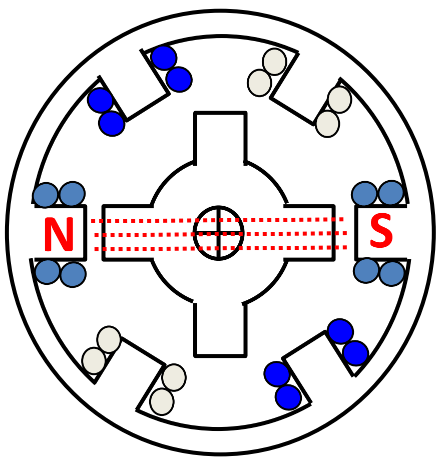
VARIABLE RELUCTANCE (VR) STEPPER

Replace the permanent magnet rotor with a (non-magnetized) toothed ferromagnetic rotor that has a lower reluctance than air.



VARIABLE RELUCTANCE (VR) STEPPER

Lines of magnetic flux pass more easily through ferromagnetic rotor than air. Hence, rotor turns to align with magnetic field. (Similar to a compass aligning with earth's magnetic poles.)



Rotor motion and holding torque result from this minimization of magnetic reluctance between stator and rotor poles.

Other rotor teeth do not align with remaining stator windings, as they are not energized.

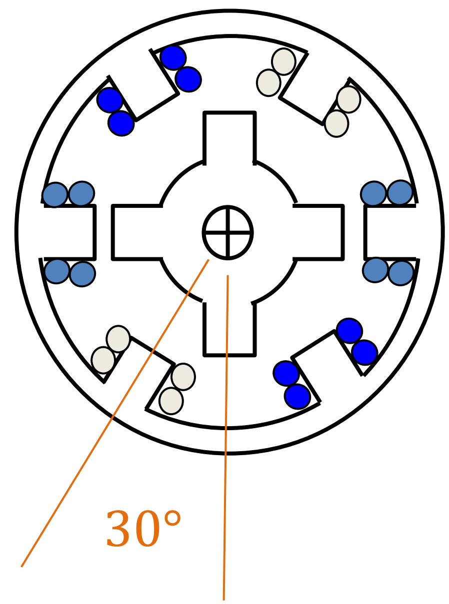
VARIABLE RELUCTANCE (VR) STEPPER

Let N_s = # of teeth on the stator

N_r = # of teeth on the rotor

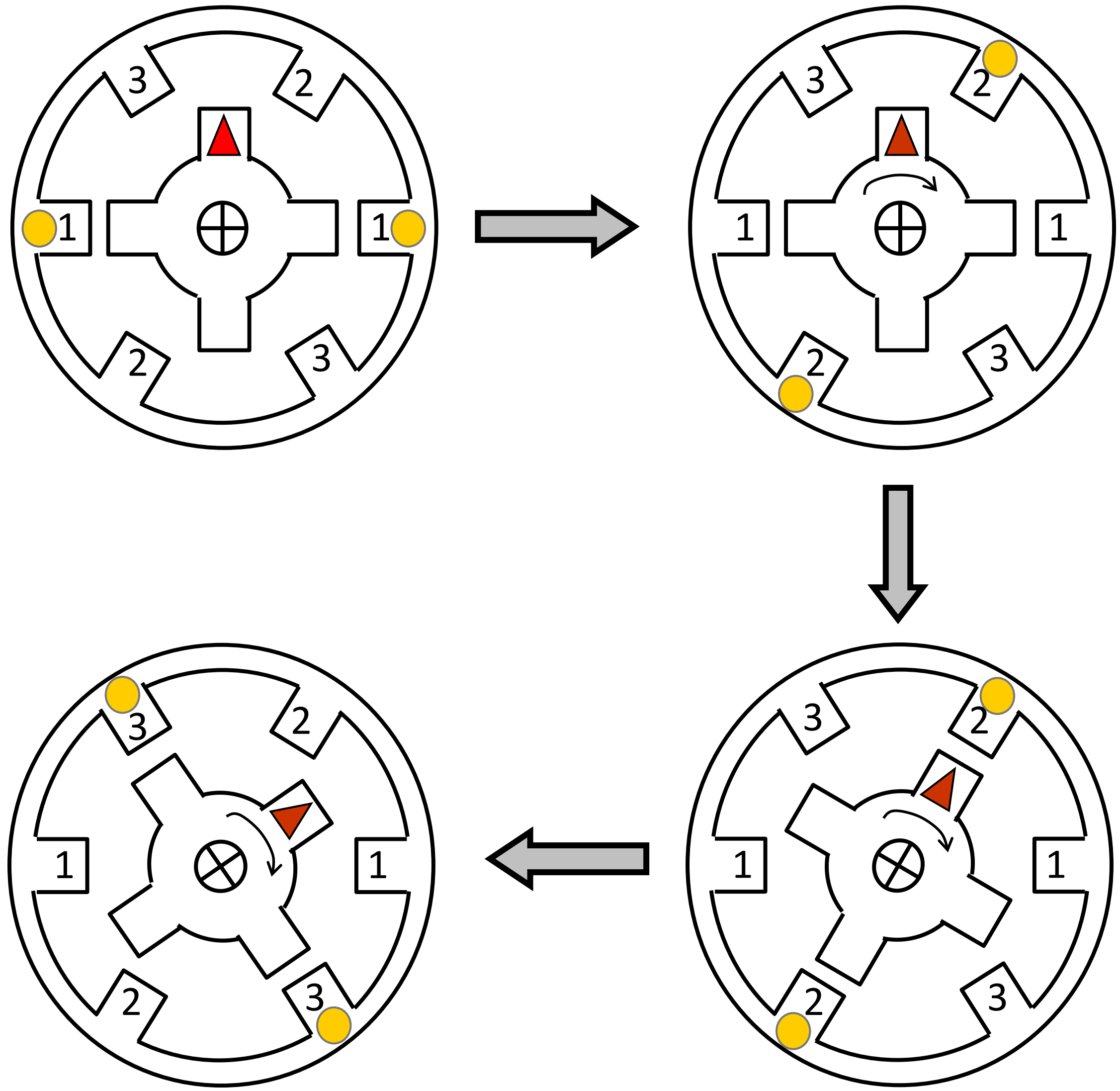
β = step angle in degrees

$$\beta = \frac{|N_s - N_r|}{N_s \cdot N_r} \times 360°$$



VARIABLE RELUCTANCE (VR) STEPPER

Step Sequence



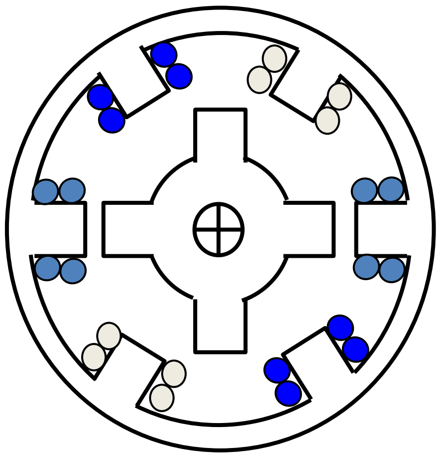
VARIABLE RELUCTANCE (VR) STEPPER

Advantage:

- Lower rotor inertia results in faster dynamic response than PM or hybrid stepping motors.

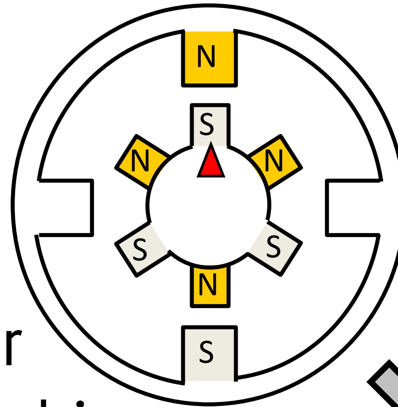
Disadvantage:

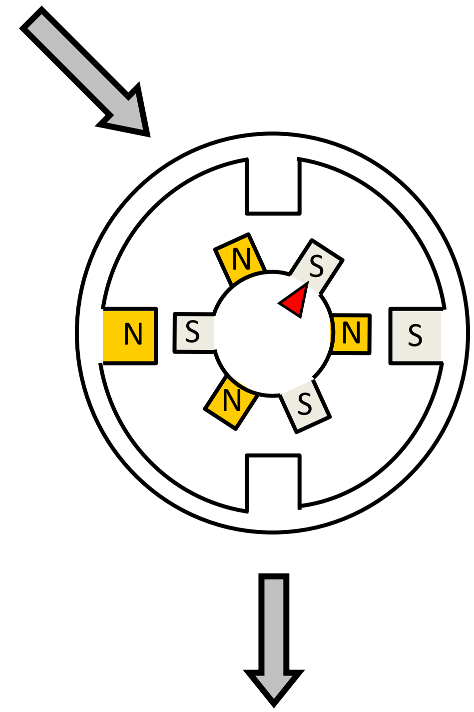
- Low allowable load inertia.
- No holding torque when the windings are not energized – no detent torque.



HYBRID STEPPER

Multi-toothed stator and rotor. The rotor has an axially magnetized magnet around its non-magnetic stainless shaft.

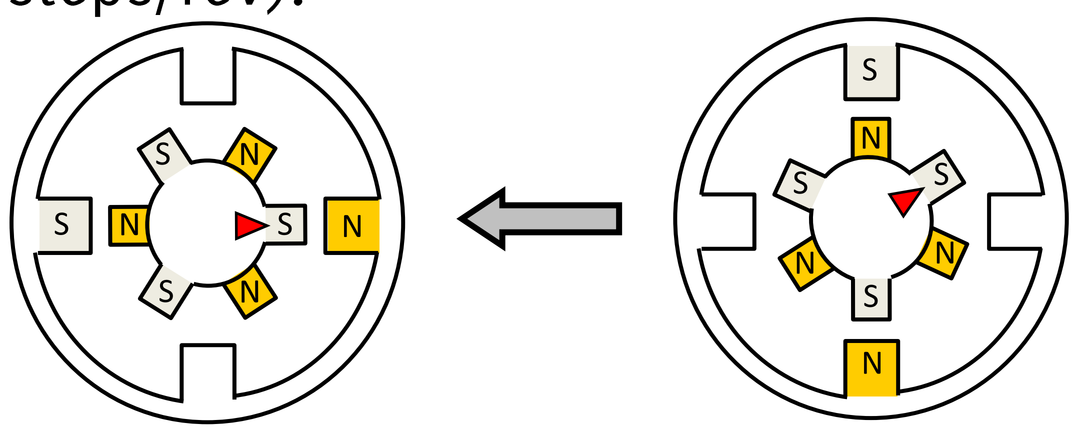




The configuration is a mixture of the variable-reluctance and the permanent-magnet type construction.

High accuracy and high torque with extra cost.

Standard step size of 1.8° (200 steps/rev).



STEPPER/BRUSHLESS DIFFERENCES

Comparison adopted from: http://www.automotsys.com.au/stepserv.html

Feedback

Brushless servomotors run in closed-loop mode, requiring a feedback device. Stepper motors do not require feedback.

Accuracy

If an unexpected load is encountered, a brushless motor will correct its position. A stepper motor will not recognize when its torque limit has been exceeded.

Speed

Brushless servomotors can run at much higher speeds (3000 to 6000 rpm) than steppers (1500 to 3000 rpm), and are not subject to the overheating phenomenon seen in steppers.

Simplicity

Stepper systems are easier to maintain because there are no feedback devices.

STEPPER/BRUSHLESS DIFFERENCES

Comparison adopted from: http://www.automotsys.com.au/stepserv.html

Cost

When comparing systems of the same torque capacity, a stepper system costs less than a brushless servo system.

Inertia Sensitivity

Brushless servomotors are more sensitive than stepper motors to fluctuations in load mass.

Shaft Power

The largest stepper motors can deliver around 2000 W of shaft power. Brushless servomotors are capable of providing much higher power.

Resolution

Brushless servomotors usually have resolutions between 500 and 4000 counts/rev. Stepper motors are manufactured with nominal resolutions of 200 steps/rev. However, some stepper drives can achieve resolutions of 50000 pulses/rev.

STEPPER/BRUSHLESS DIFFERENCES

Comparison adopted from: http://www.automotsys.com.au/stepserv.html

Digital Control

Stepper motors are well-suited to digital control. Most brushless servomotors use an analog controller and resolver or encoder feedback, requiring a more sophisticated and costly controller.

Standardization

Nearly all stepper motors conform to the NEMA flange dimensions so they can be easily be replaced, even between different brands.

Noise

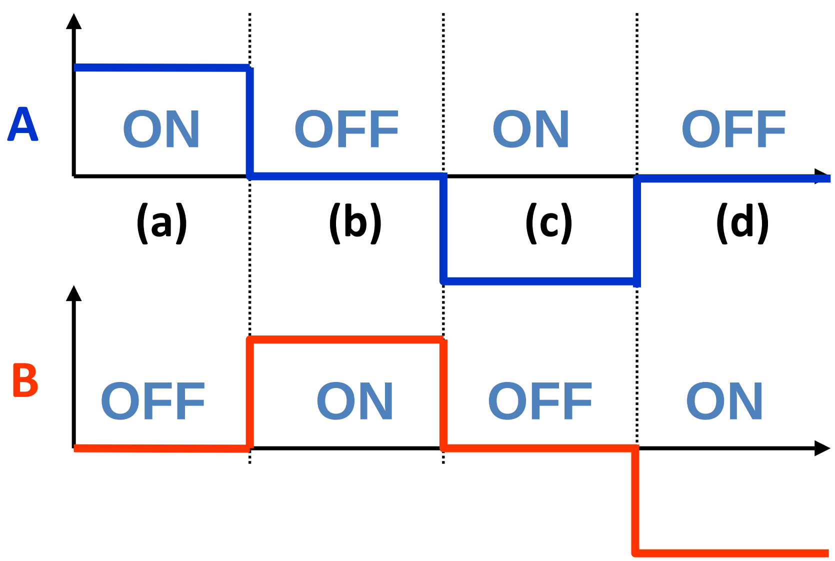
Stepper motors are inherently noisy, while brushless servomotors don't exhibit this problem.

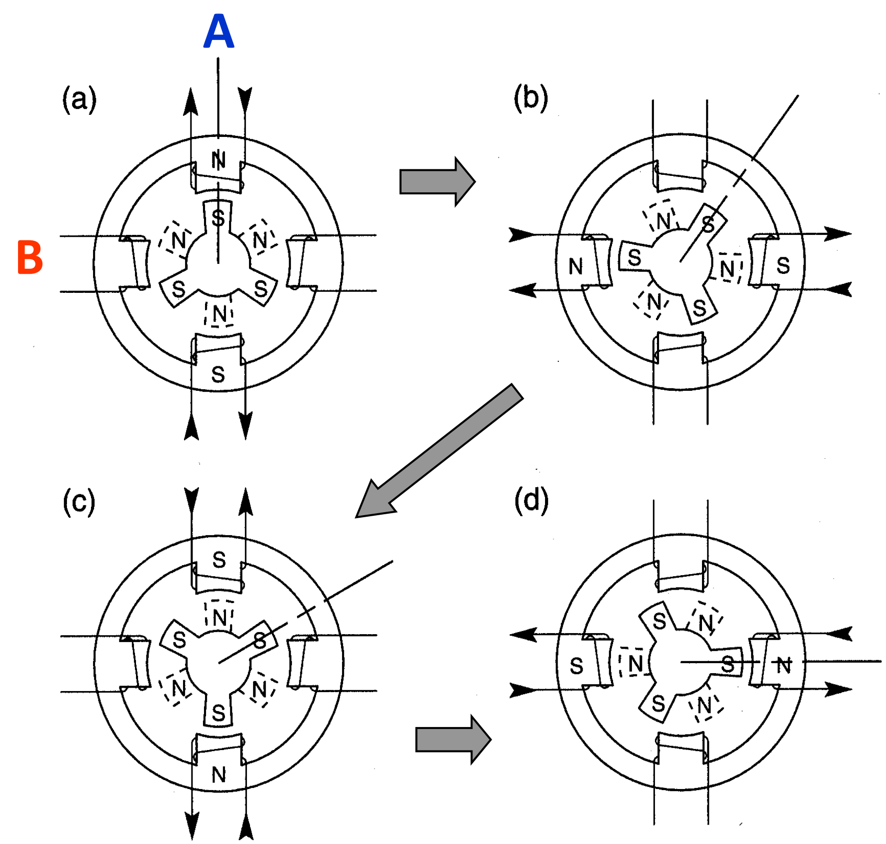
Power Consumption

Stepper motors apply full rated motor current through the motor windings, no matter the applied load. A servomotor only consumes current as needed to achieve desired rotor positioning.

WAVE DRIVE SEQUENCE

Full Stepping, One Phase On

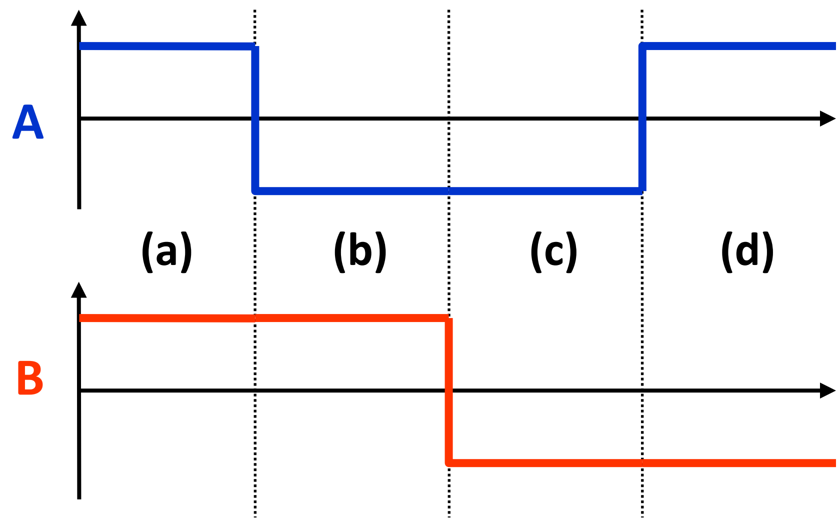


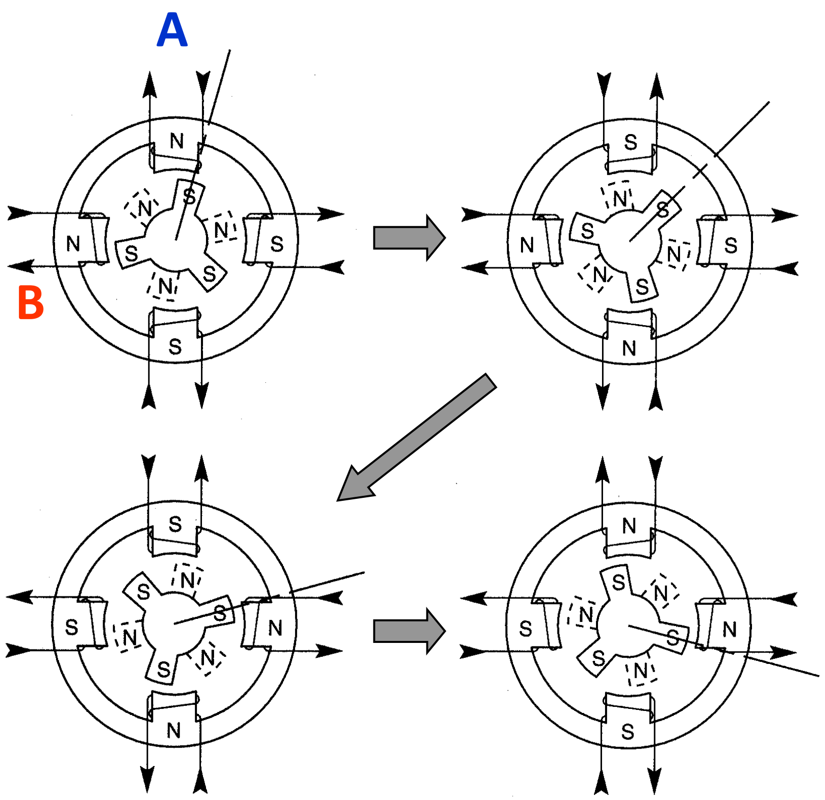


- Not all windings are used at any one time
  - Produces less than maximum torque

FULL STEP DRIVE SEQUENCE

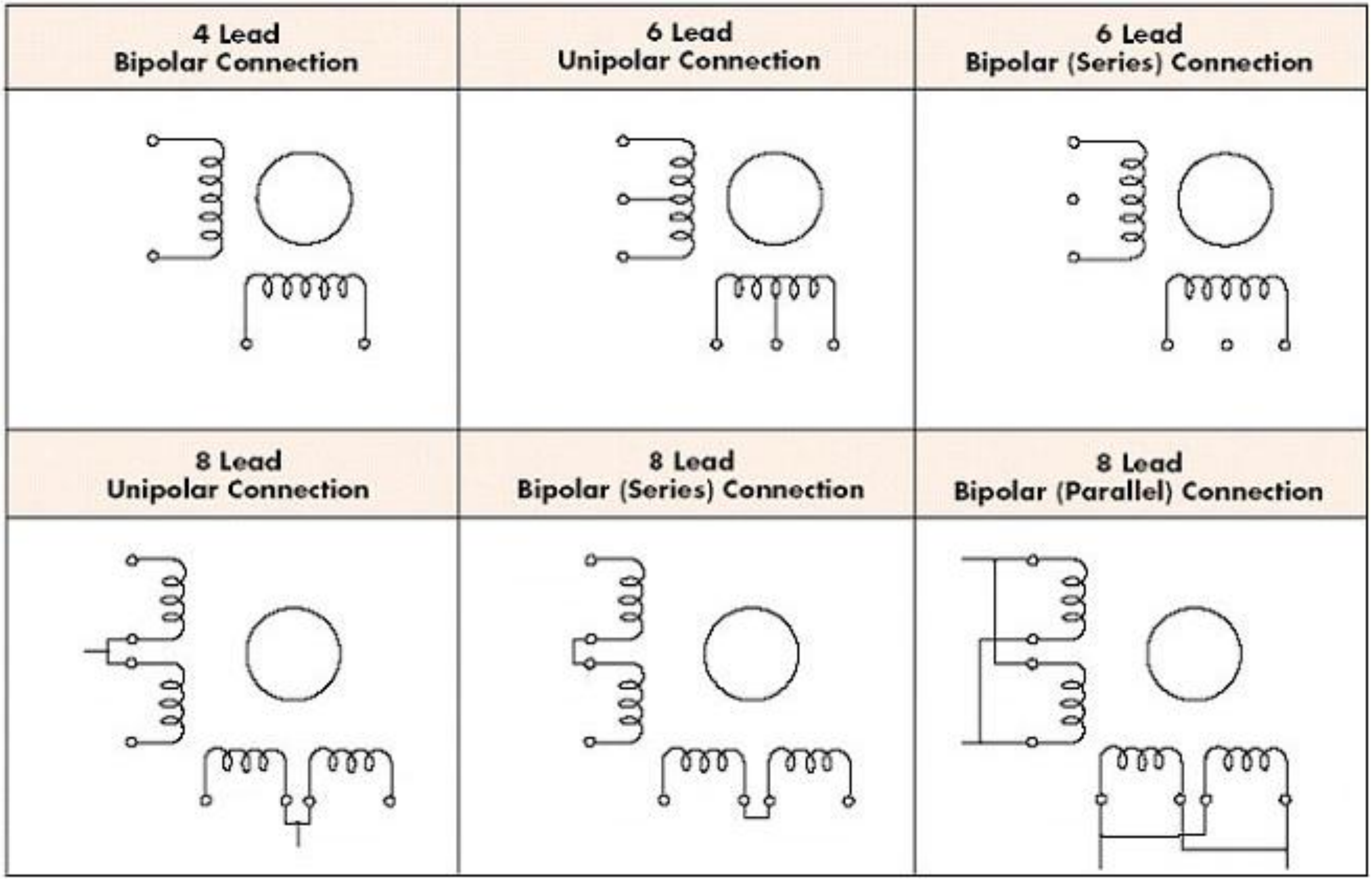
Full Stepping, Two Phases On



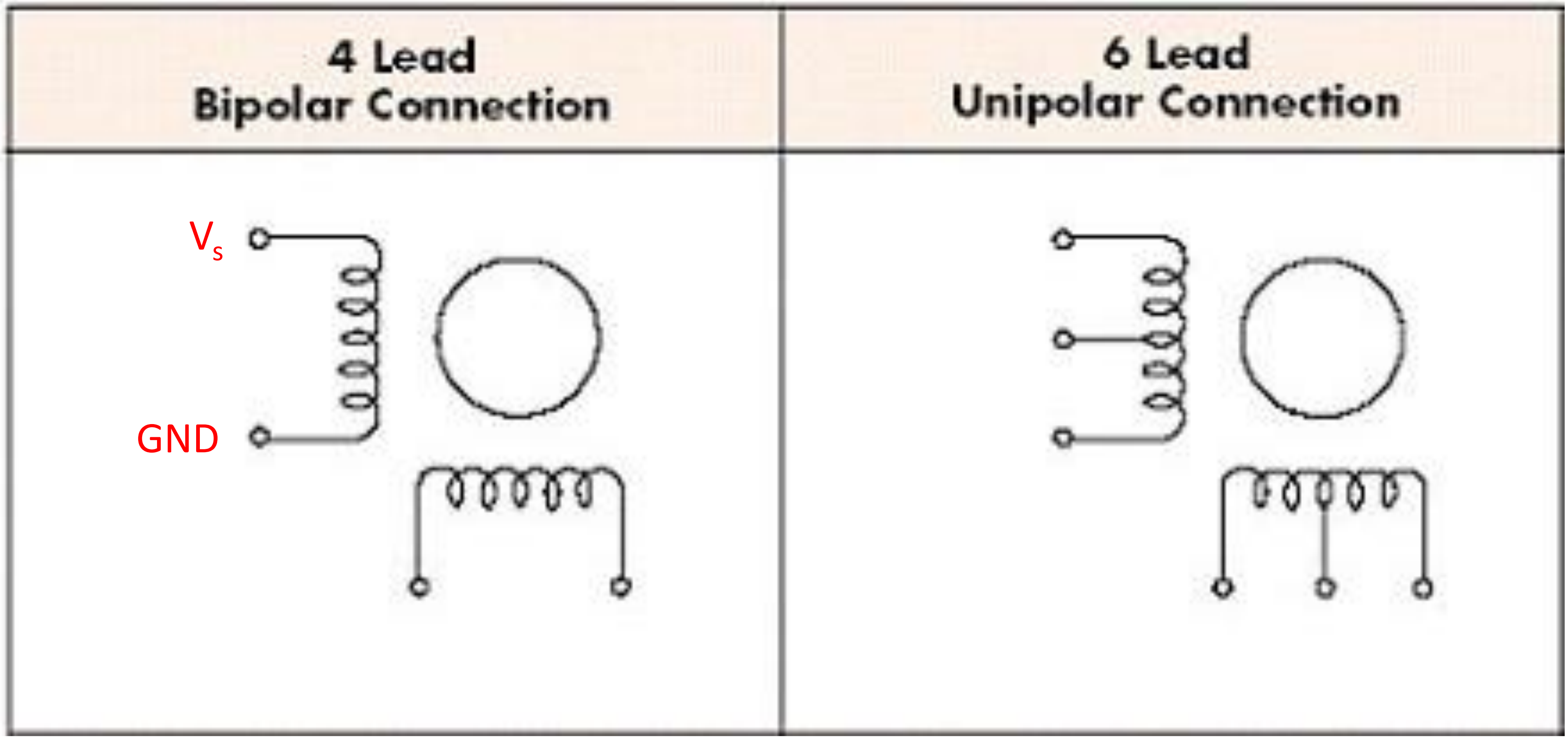


Able to use all windings in "bipolar" mode to achieve maximum torque

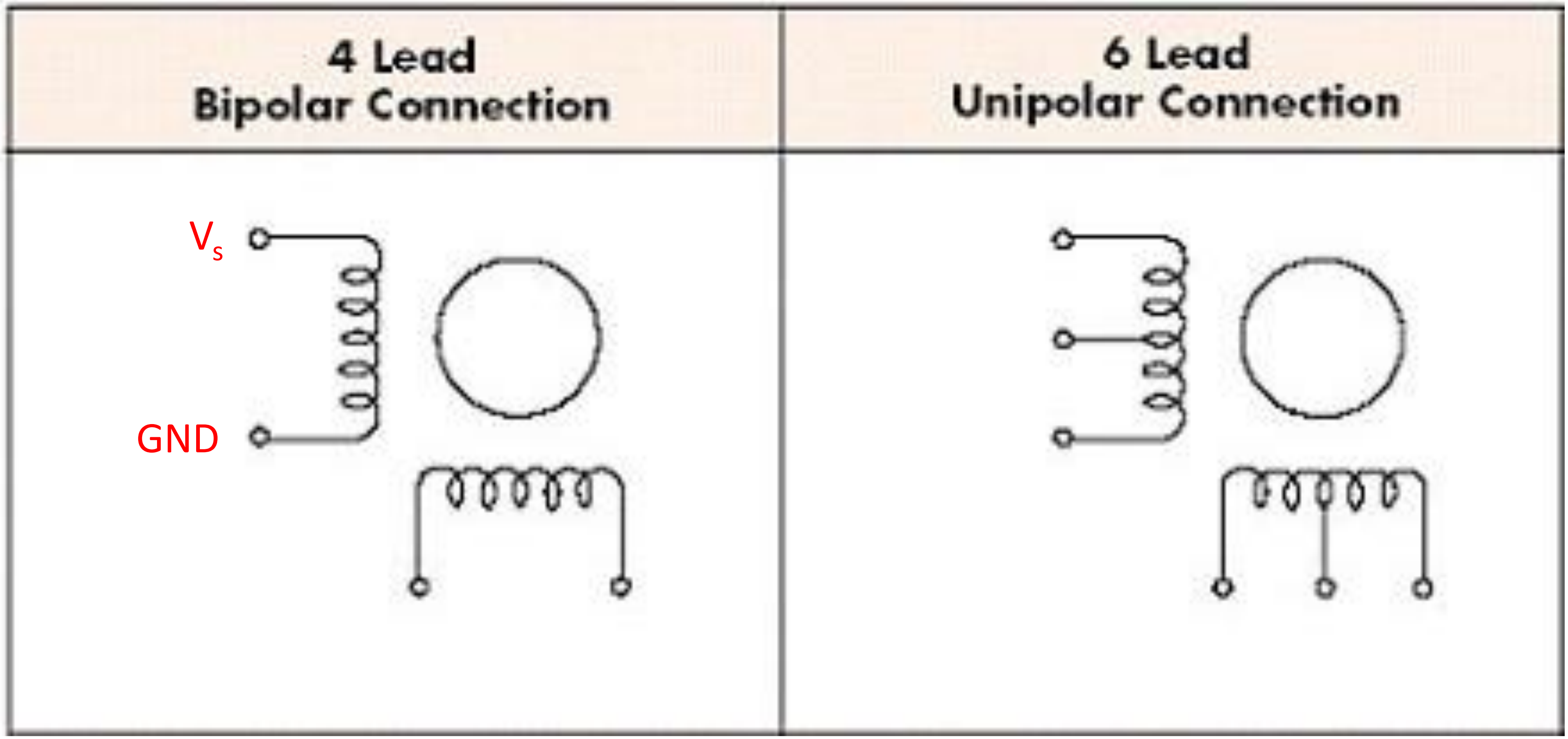
UNIPOLAR AND BIPOLAR OPERATION



UNIPOLAR AND BIPOLAR OPERATION

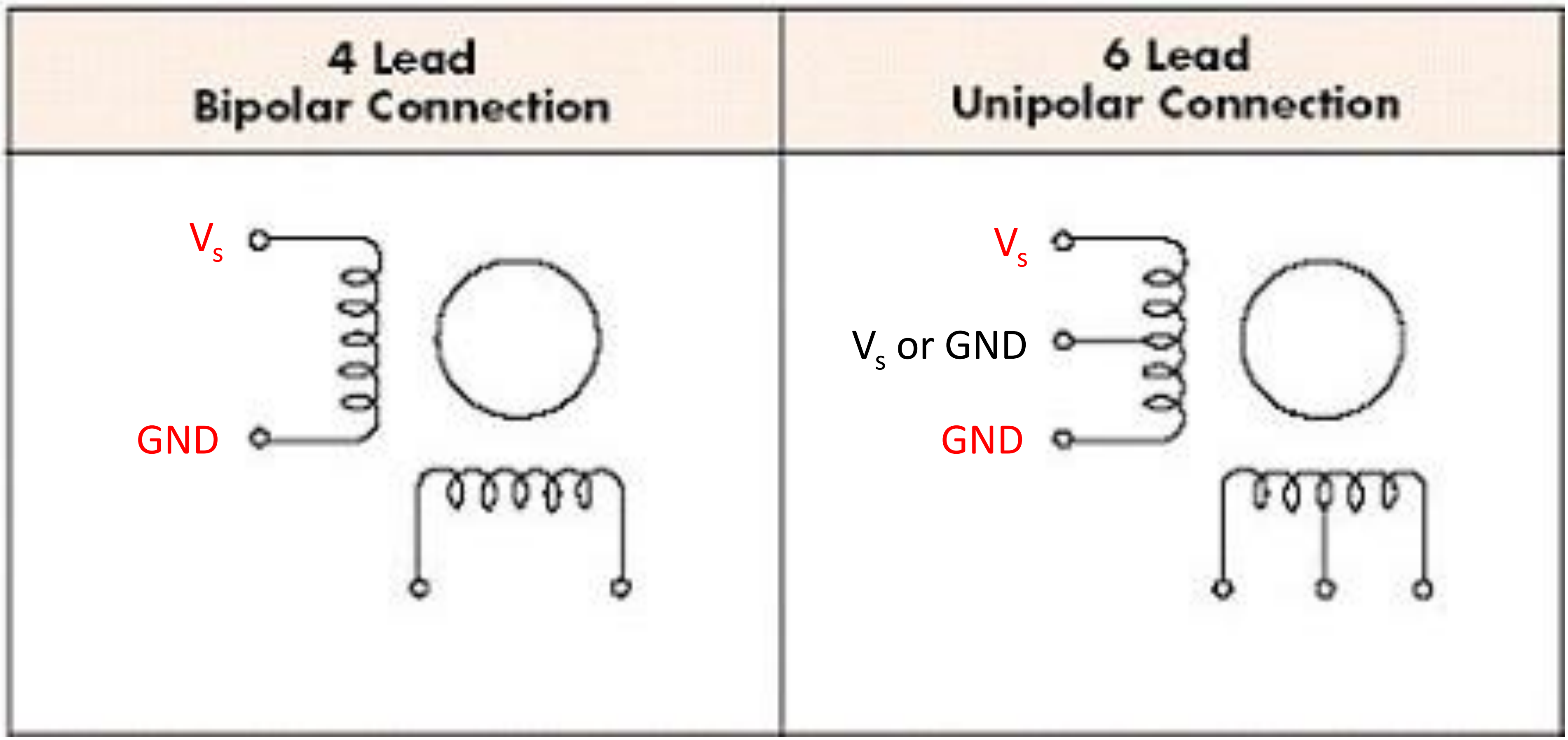


UNIPOLAR AND BIPOLAR OPERATION



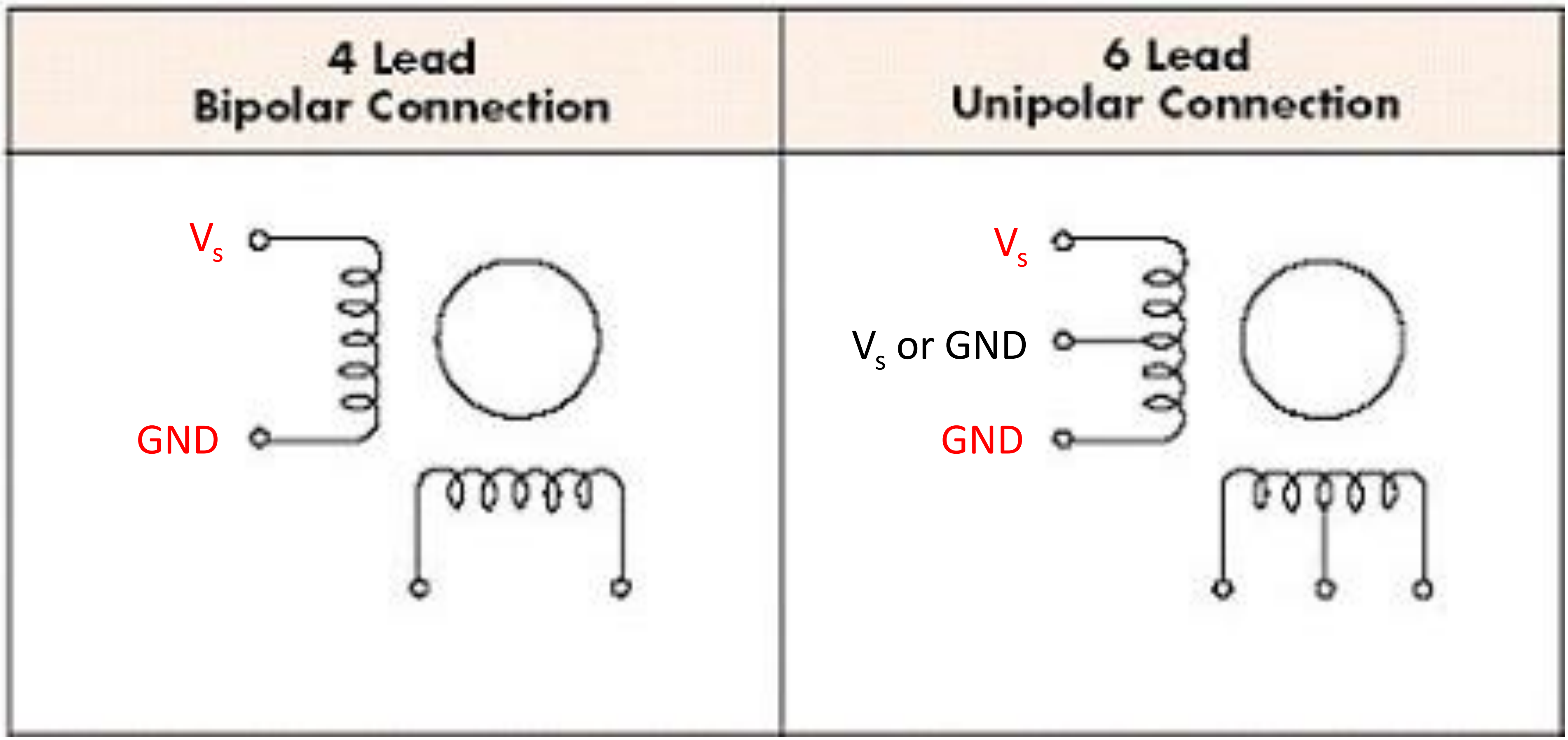
Have to swap leads to reverse magnetic polarity

UNIPOLAR AND BIPOLAR OPERATION



Have to swap leads to reverse magnetic polarity

UNIPOLAR AND BIPOLAR OPERATION



Have to swap leads to reverse magnetic polarity

No lead swapping, but less torque production

UNIPOLAR AND BIPOLAR OPERATION

Bipolar

- Current through winding must be reversed $\Longrightarrow$ needs an H-bridge!
- Greater torque, but more complex circuitry

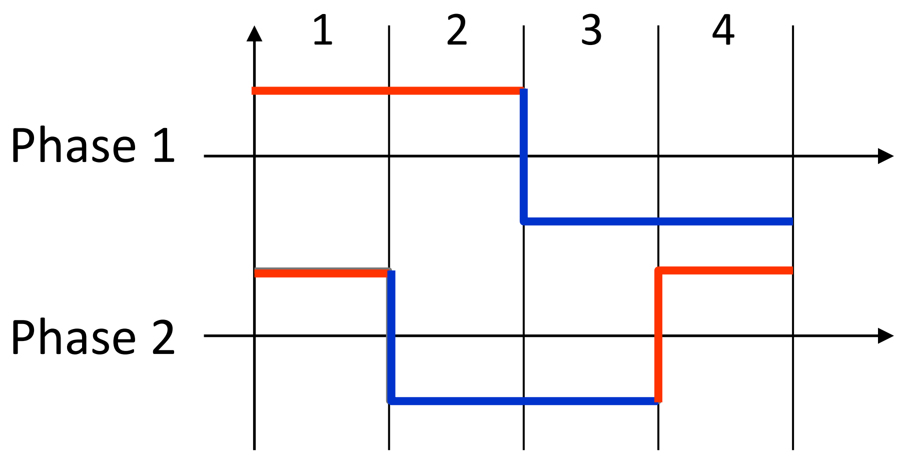
Unipolar

- Simple circuitry, but less torque
- Thinner wire => more resistance => more power loss

On the same frame, bipolar motors can deliver about 40% more torque than unipolar motors

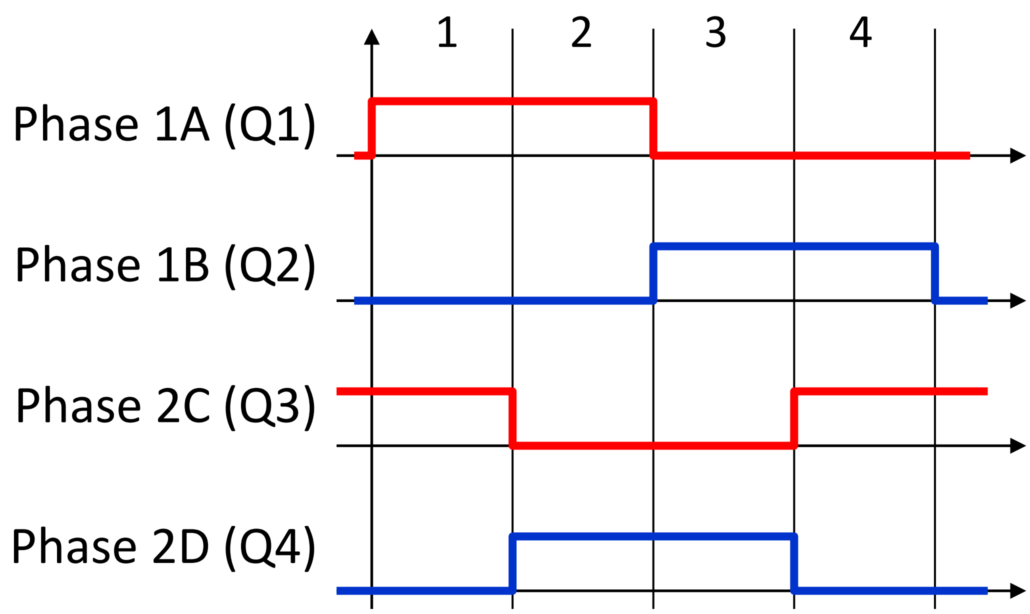
UNIPOLAR AND BIPOLAR OPERATION

Full Step Sequence, Two Phase On with Bipolar Drive

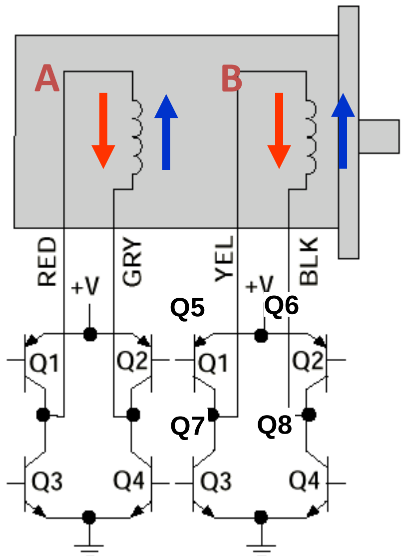


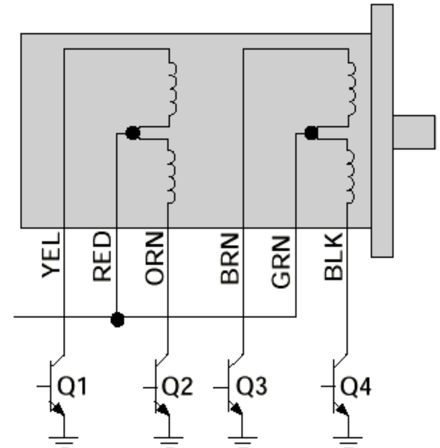
UNIPOLAR AND BIPOLAR OPERATION

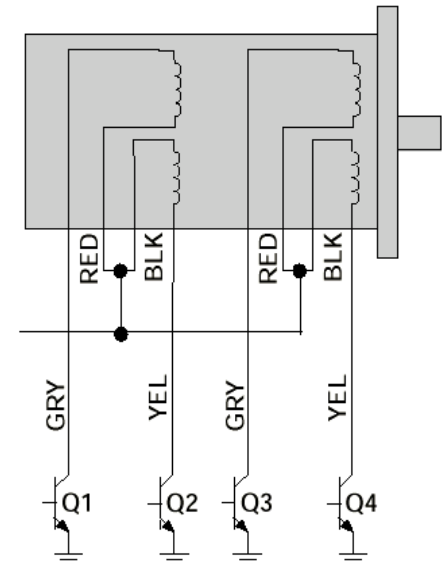
Full Step Sequence, Two Phase On with Unipolar Drive

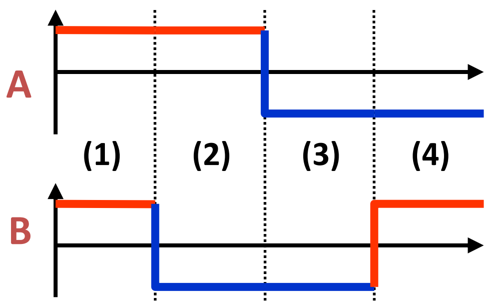


UNIPOLAR AND BIPOLAR OPERATION









BIPOLAR

CW ROTATION ↓ / CCW ROTATION ↑

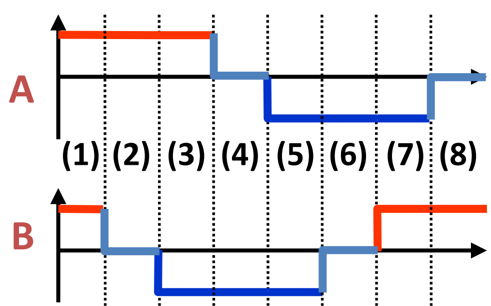
Step	Q_1-Q_4	Q_2-Q_3	Q_5-Q_8	Q_6-Q_7
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF

Normal 4-Step Sequence

UNIPOLAR

CW ROTATION ↓ / CCW ROTATION ↑

Step	Q_1	Q_2	Q_3	Q_4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	ON
3	OFF	ON	OFF	ON
4	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF



CW ROTATION ↓ / CCW ROTATION ↑

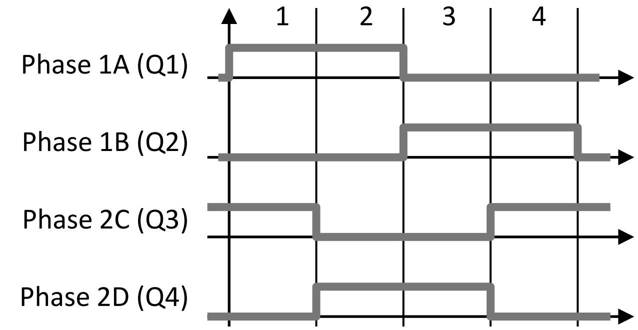
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

½ Step 8-Step Sequence

CW ROTATION ↓ / CCW ROTATION ↑

1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

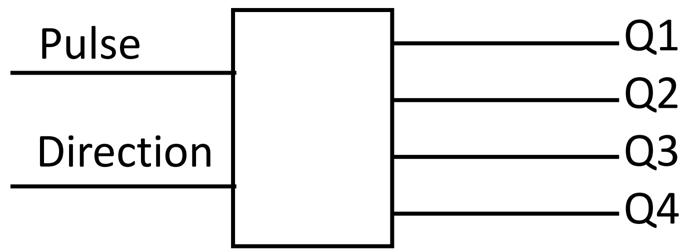
PULSE EXCITATION



Logic circuit can make driving (controlling) stepper motor easier:

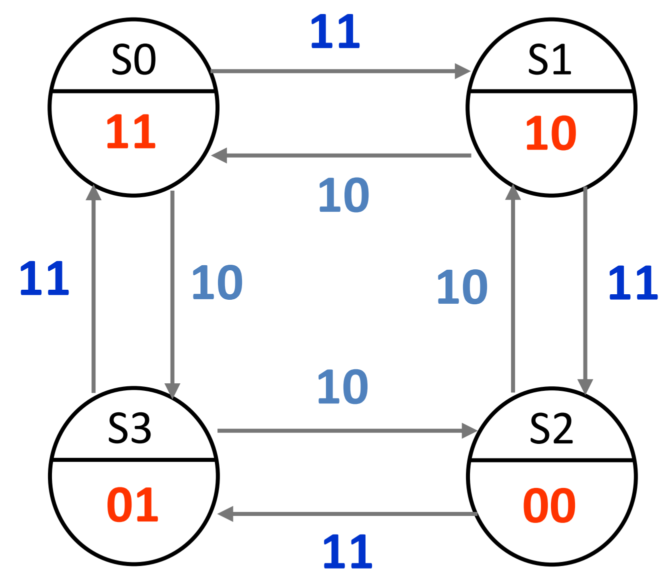
- Pulse causes step
- Direction of step controlled by logic level signal
- Only two output variable is needed, since

$$Q2 = \overline{Q1} \quad \text{and} \quad Q4 = \overline{Q3}$$



Input: P & D

Output: Q1 & Q3

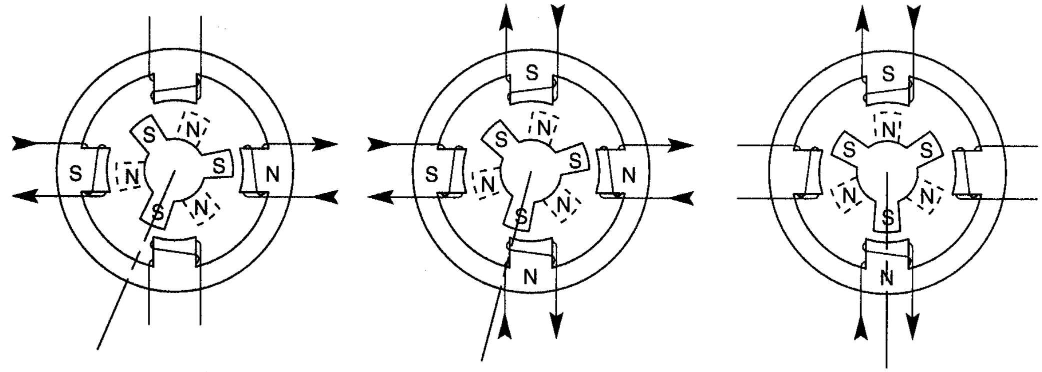


- Pulse signal must be longer than the state machine clock. Otherwise additional logic must be designed to detect edges.

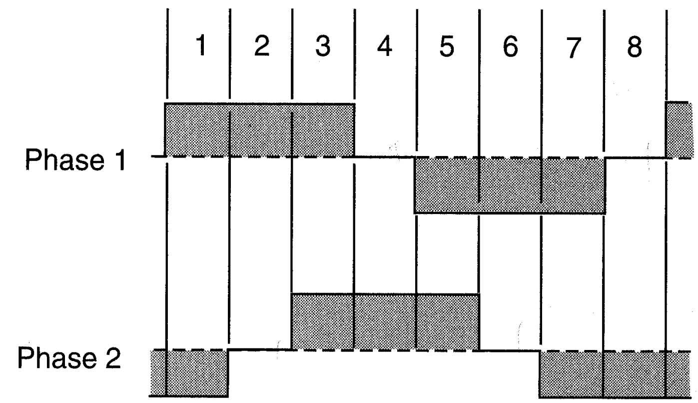
Alternative arrangement – use the pulse signal as the clock.

- The pulse signal will be eliminated from the transition condition.

HALF STEPPING SEQUENCE

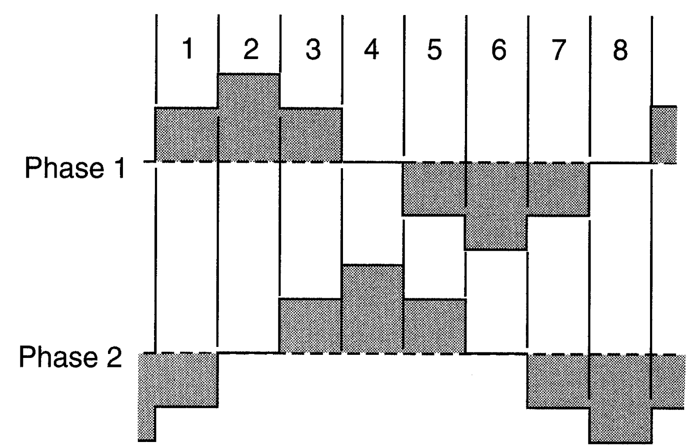


If a complete coil set is turned off rather than reversed, the rotor will move one-half of a step:



The holding torque at the half-step position is less than that at the full step position (about 3/4), i.e. alternate steps will be strong and weak.

- To produce approximately equal torque on every step, we can apply higher current level when only one phase is energized:



MICRO-STEPPING SEQUENCE

If half-step is possible, why not smaller steps?

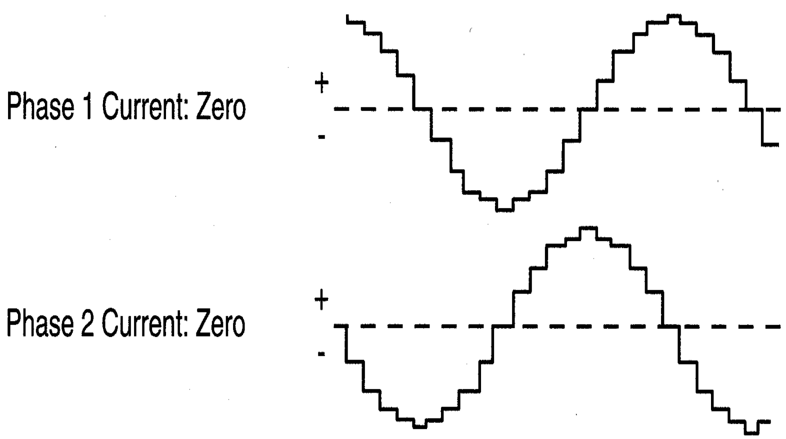
Full and half step sequence can be viewed as crude approximation to sine/cosine quadrature signals.

Application of true sine/cosine current profile to the two phases will give arbitrarily small step size -- Micro-Stepping.

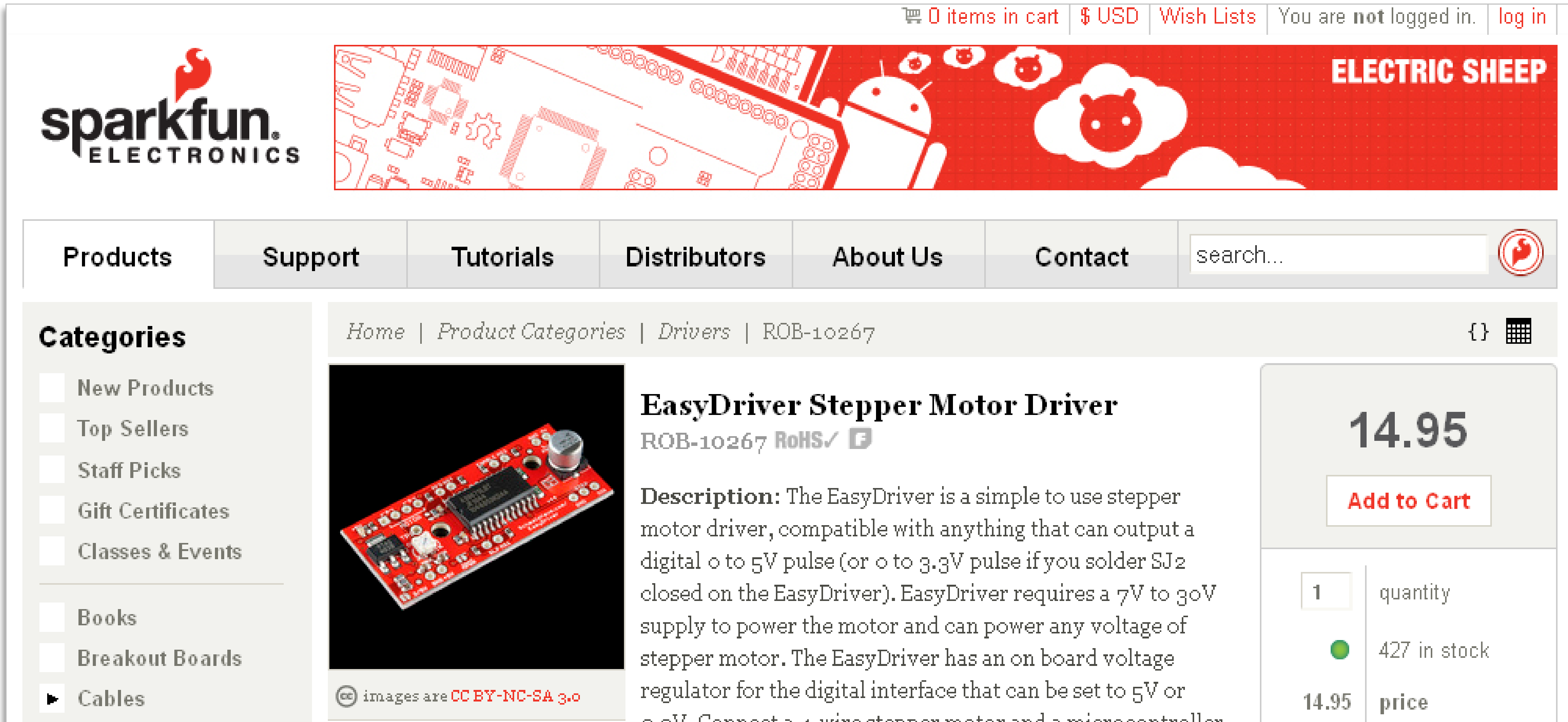
The size of the micro-steps depends only on the discretization size of the sine/cosine wave.

Disadvantages:

- Holding torque varies.
- Requires proportional amplifier.
  - Switching amplifier is more efficient, cooler.
  - PWM can be used for proportioning so that a switching amplifier can still be used.



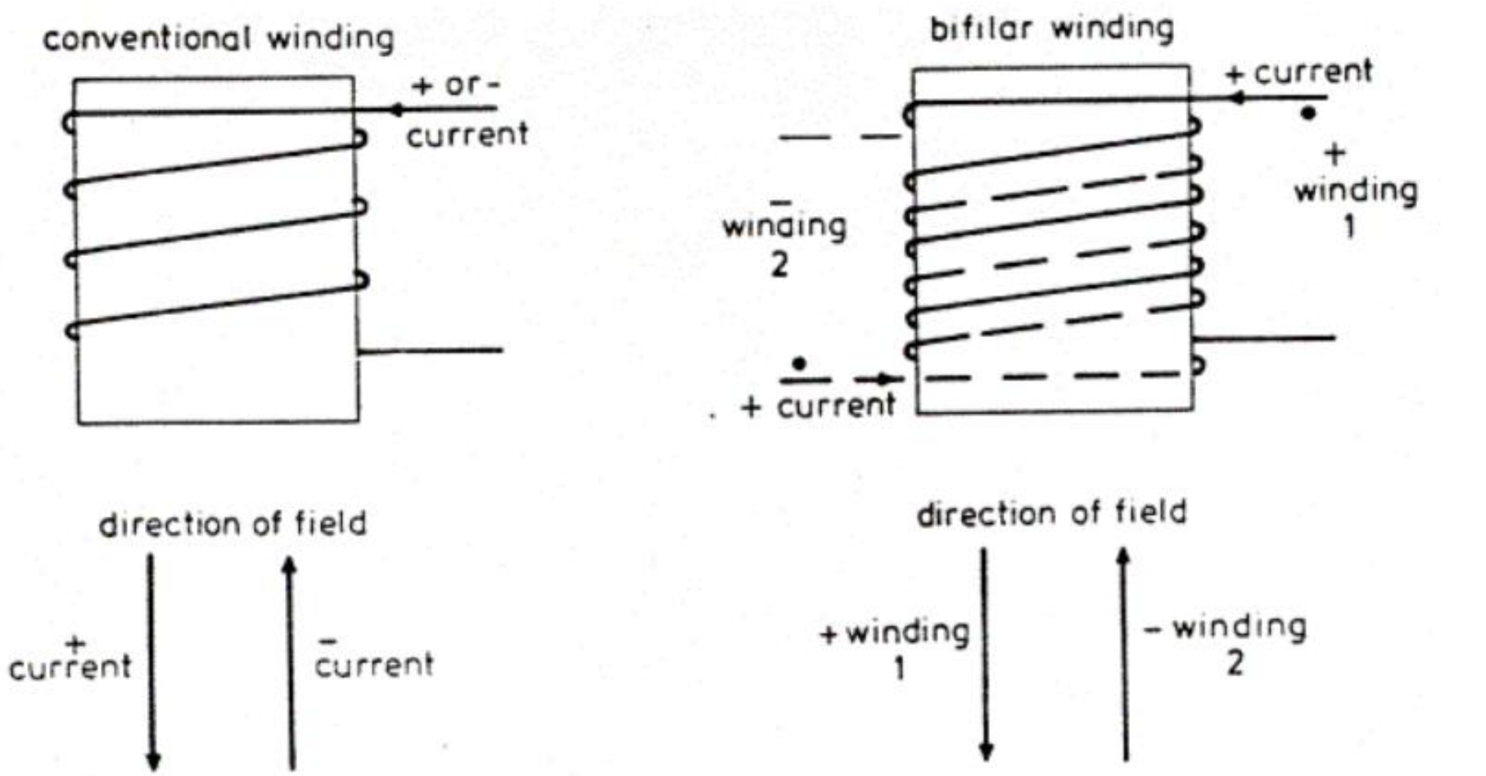
STEPPER MOTOR DRIVERS



WINDING CONFIGURATION

Most stepper motors are “bifilar wound,” which means that there are two identical sets of windings on each pole.

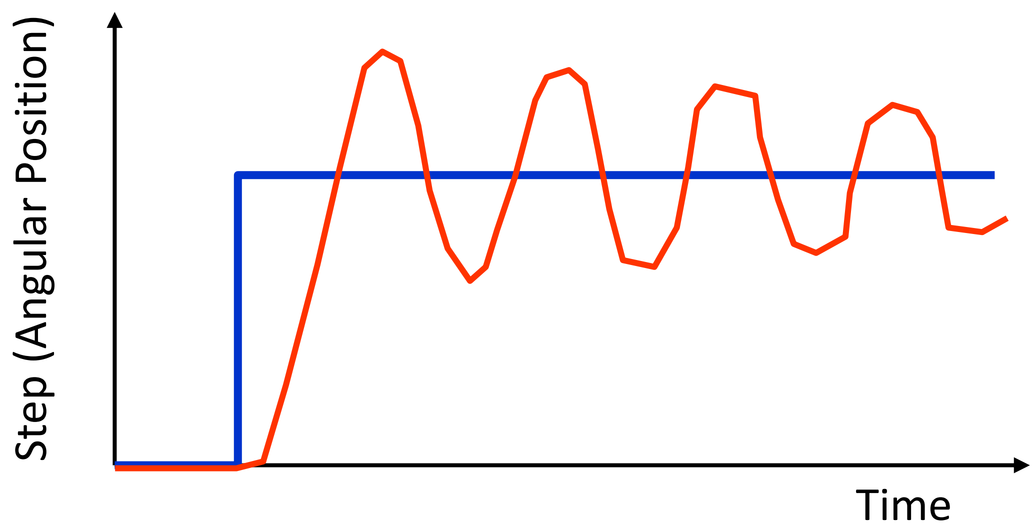
Bifilar windings were originally designed for unipolar drives. Rather than reverse the current in one winding (bipolar), the field may be reversed by transferring current to another coil wound in the opposite direction (unipolar).



STEPPER MOTOR PERFORMANCE

Single Step Response

- When a stepper motor performs a single step move, the response is oscillatory.
- Lightly damped mass-spring-damper response:
  - Rotor inertia plus load inertia is the mass,
  - Magnetic field is the nonlinear spring, and
  - very little damping (provided by the motor).



STEPPER MOTOR PERFORMANCE

Resonance

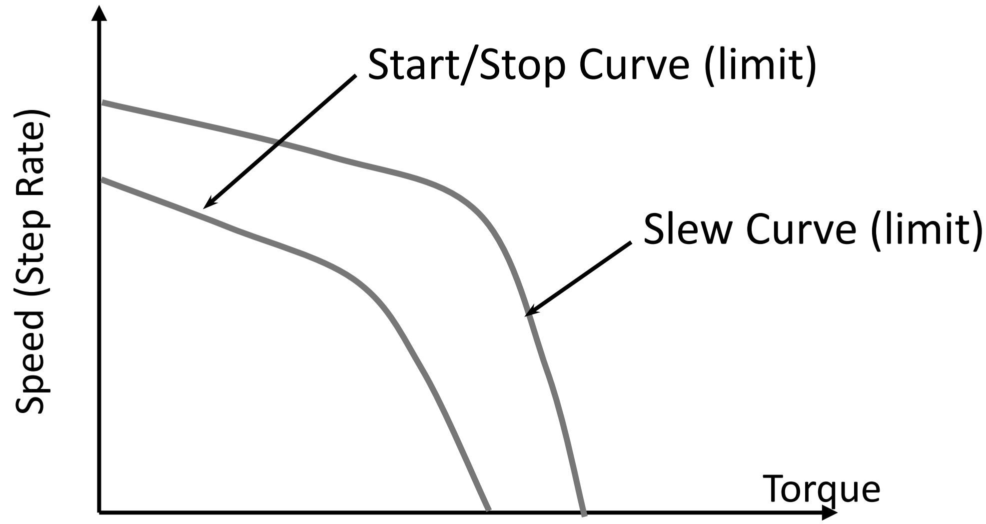
- Stepping the motor at its natural oscillation frequency will cause an exaggerated response – *resonance*.
- It is the major difficulty for stepper motor actuated systems.
- Can also excite structural resonance in the surrounding mechanical components.
- When operating at resonance, the stepper motor will not step properly — *desyncronizing* or *stall*.
- Remedy:
  - Avoiding step rates near the resonance (may switch between full/half stepping)
  - Adding mechanical damping.

STATIC OPERATION

Holding Torque

- The maximum torque can be applied to the rotor of the motor without moving the rotor position.
- Motor will "slip" if the applied external torque exceeds the maximum rated holding torque.
  - PM steppers will slip in four step increments.
  - With open-loop operation (no feedback of position), system position accuracy is lost!
- PM stepper exhibits *detent torque* – small holding torque present when no power is supplied to the motor.
  - Due to the magnetic field generated by the permanent magnets.
- Depends on application, holding torque can be good, bad or inconsequential.

TORQUE SPEED CURVE



The chart is load dependent.

Operation above the start/stop limit requires ramping up the speed from under the start/stop limit.

- The stepping speed (rate) is slowly brought up to the operating speed.
- To stop, the speed is slowly brought down below the start/stop curve before stopping.

For a heavier load, a lower acceleration rate is used.

THERMAL CHARACTERISTICS

Temperature is a major performance limitation.

When motor is stopped, current flow through the windings are at maximum $\rightarrow$ most heat is generated via resistive heating.

- Positioning applications tends to spend most time "sitting still."
- At idle, the rotor is not moving, cooling is also limited.
- To reduce temperature rise during idling, winding current is usually reduced to lower resistive heat generation.

Motor temperature rating are based on the thermal breakdown temperature of the winding wire insulation.

At steady-state, the rated current is applied to achieve rated holding torque.

During transient (current reversal), voltage increases substantially to overcome the inductance effect – since duration is short, temperature is not affected substantially.

COMING UP…

System Interfacing (Communication)