Stepper Motors Uncovered (1)

Part 1: stepper motor fundamentals

By Timothy G Constandinou

Stepper motors, and in particular the way they must be driven, continue to riddle many of our readers. This two-part article is a solid base for your understanding of stepper motor operation as well as practical use. Next month, the article culminates in the construction of a high-power 4-channel motor driver with PC control.

Often a mechanical operation is required in an application to accurately position a load or device. While a conventional DC or AC motor can be used, it is difficult to determine the exact position of the load, motor speed, or how much total motion has been produced, unless external positioning sensors, encoders, servo loops, and controlling devices (brakes or clutches) are used.

The preferred alternative is to use a stepper motor. This is an electromechanical device, which converts pulses into discrete mechanical movements.

Typical stepper motor applications…

include computer peripherals (scanners, disk drives, printers, etc), cameras, telescopes and satellite dish positioning systems, medical applications, robotics, barcode scanners and numerically controlled machine tools.

Types of stepper motors

At first blush stepper motors seem to differ only in respect of size, weight and the number of wires or connecting pins. A suggested classification is given below.

Variable reluctance (Figure 1)
This type of motor does not use a permanent magnet. As a result, the rotor can move without constraint or 'detent' torque. This type of construction is the least common and is generally used in applications that do not require a high degree of torque, such as the positioning of a micro slide.

Permanent magnet (Figure 2)
Also referred to as a 'canstack' or 'tincan' motor, this device has a permanent magnet rotor. It is a relatively low speed, low torque device with large step angles of either 45 or 90 degrees. The simple construction enables these motors to be produced at low cost, making them the ideal choice for low power applications,

Features of Stepper Motors

- Rotation angle is proportional to number of input pulses.
- Rotational speed is proportional to the frequency of input pulses.
- Open loop system with no position feedback required.
- Excellent response to acceleration, deceleration and step commands.
- Non-cumulative positioning error (±5% of step angle).
- Excellent low speed and high torque characteristics without need for gear reduction.
- Holding torque when energized.
- Inherent detent torque.
- Bi-directional operation.
- Can be stalled without motor damage.
- No brushes for longer trouble free life.
- Precision ball bearings (depending on brand/type).

Drawbacks of Stepper Motors

- Resonances can occur if not properly controlled.
- Not easy to operate at extremely high speeds.
- If overtorqued, all knowledge of position is lost and system must be reinitialized.
- Produces much less torque, for a given size than the equivalent DC/AC motor.

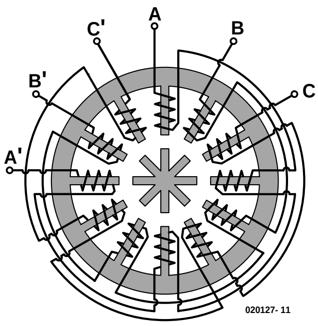

Figure 1. Variable-reluctance stepper motor.

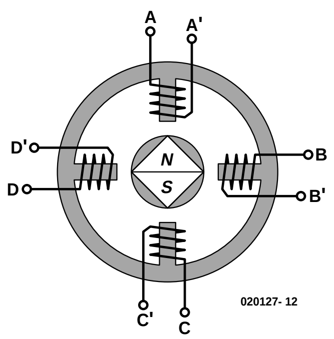

Figure 2. Permanent-magnet stepper motor.

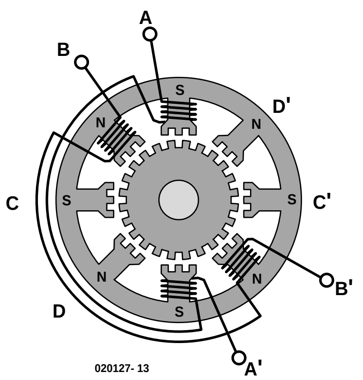

Figure 3. The hybrid stepper motor is a clever combination of the variable-reluctance and permanent-magnet types.

such as in inkjet printers.

Hybrid (Figure 3)

This combines the best characteristics of the variable reluctance and permanent magnet motors. They are constructed with multi-toothed stator poles and a permanent magnet rotor. Hybrid motors are available with step resolutions of 0.9°, 1.8° or 3.6°, the standard being 1.8°. Because they exhibit high static and dynamic torque and run at very high step rates, hybrid motors are the preferred type for industrial applications.

Size

Generally stepper motors are classified according to their frame size (body diameter). For example, a size 23 stepper motor has a body size of approximately 2.3 inches. The most common frame sizes are 11, 17, 23, 34 and 42.

Power

Power levels for stepper motors range typically from a few hundred milliwatts (for smaller motors) up to several watts (for larger motors). The maximum power dissipation of a stepper motor is determined by the thermal limits of the windings in the motor. This is seldom clearly stated in the motor manufacturer's data. To determine this we must apply the relationship $P = VI$. For example, a size 23 step motor may be rated at 6 V and 1 A per phase. Therefore with two phases energized the motor has a rated dissipation of 12 watts. It is normal practice to rate a stepper motor at the power dissipation level where the motor case rises to 65 °C above the ambient temperature. Therefore, if the motor can be mounted to a heatsink it is often possible to increase the allowable power dissipation.

More aspects of stepper motors

What else do we need to know about the stepper motor before we're able to make it turn and do something useful?

The Rotating Magnetic Field

When a phase winding of a stepper motor is energized with current, a magnetic flux is developed in the stator. The rotor then aligns itself so that the flux opposition is minimized. As a result, in requiring the motor to rotate, the windings must be energized in a sequence to produce a rotating magnetic flux.

Torque Generation

The torque produced by a stepper motor depends on several factors, including step rate, drive current in the windings and drive design or type.

In a stepper motor a torque is developed when the magnetic fluxes of the rotor and stator are displaced from each other. The stator is made up of a high permeability magnetic material, which results in the magnetic flux being confined to the stator structure. This serves to concentrate the flux at the stator poles. The torque produced by the motor is proportional to the intensity of the magnetic flux generated when the winding is energized.

Phases

The number of different paths for the magnetic flux to flow in is referred to as the number of phases of the motor.

- Generally, stepper motors have two phases even though motors exist with three or five phases.

– A bipolar motor has one winding per phase.
– A unipolar motor has a winding with a centre-tap, or two separate windings per phase.

Winding Connections
Stepper motors are produced in a number of different lead configurations. The most popular are:

Stepper Leads	Connection Schemes
4 Lead	Bipolar
5 Lead	Unipolar
6 Lead	Unipolar Bipolar (series connected)
8 Lead	Unipolar Bipolar (series connected) Bipolar (parallel connected)

The associated wiring diagrams are given in **Figure 4**.

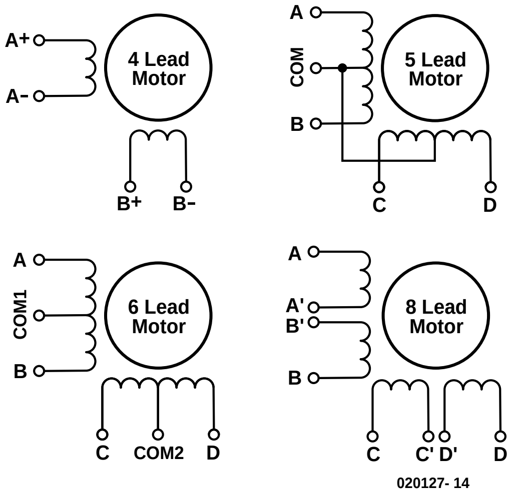

Figure 4. Basic connections of 4-, 5-, 6- and 8-lead motors.

Poles
A pole can be defined as one of the regions in a magnetized body where the magnetic flux density is concentrated. Usually both the rotor and stator of a stepper motor have an equal number of poles, even though this is not always the case.

Stepping Angle
The full-step angle of a stepper motor is determined by the following relationship:

$$\text{Step angle} = 360 / (n_{Ph} \times ph) = 360 / n.$$

where
n_{Ph} = number of equivalent poles per phase = number of rotor poles;
ph = number of phases;
n = total number of poles (all phases).

This relationship is only valid if the number of stator and rotor poles are equal.

Stepping modes

The stepper motor can be driven in a number of different sequences. The most common of these are:

Wave Drive
In this mode only one phase is energized at any given time. For unipolar motors this means only 25% of the available windings are utilized, or 50% utilization for bipolar motors.

Order	Phase A	Phase B	Phase $\overline{A}$	Phase $\overline{B}$
1				
2				
3				
4				

Full Step Drive
In this mode two phases are energized at any given time. For unipolar motors this means 50% of the available windings are utilized, or 100% utilization for bipolar motors.

Order	Phase A	Phase B	Phase $\overline{A}$	Phase $\overline{B}$
1				
2				
3				
4				

Half Step Drive
In this mode the sequences of the wave and full-step drives are interleaved to enable the rotor to be aligned in half steps. For unipolar motors this means 37.5% of the available windings are utilized (on average) or 75% utilization for bipolar motors.

Order	Phase A	Phase B	Phase $\overline{A}$	Phase $\overline{B}$
1				
2				
3				
4				
5				
6				
7				
8				

Microstepping
The currents in the windings are continuously varied to be able to break up one full step into many smaller discrete steps. This excitation sequence will not be covered in this article.

Technical data and terminology

Holding Torque
The maximum steady torque that can be applied to the shaft of an energized motor without causing continuous rotation.

Detent Torque
The maximum torque that can be applied to the shaft of a non-energized motor without causing continuous rotation.

Speed/Torque Curve
The speed/torque characteristics of a stepper motor are a function of the drive circuit, excitation method and load inertia.

Maximum Starting Frequency
The maximum pulse rate (frequency) at which an unloaded stepper motor can start and run without missing steps, or stop, without taking more steps than pulses.

Pull-out Torque
The maximum torque that can be applied to the shaft of a step motor (running at constant speed) and not cause it to lose step.

Pull-in Torque
The maximum torque at which a step motor can start, stop and reverse the direction of rotation with-

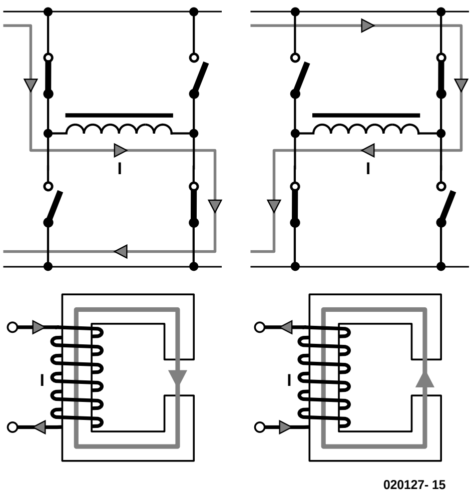

Figure 5. Bipolar drive scheme.

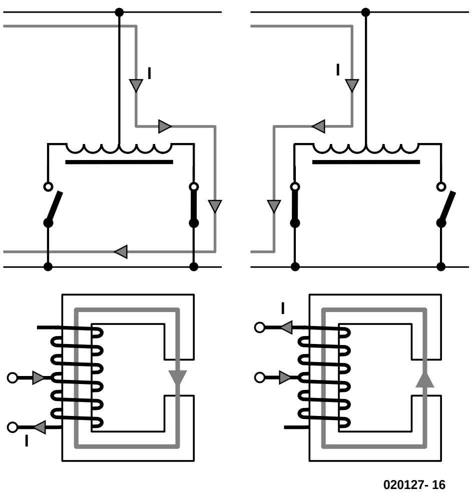

Figure 6. Unipolar drive scheme.

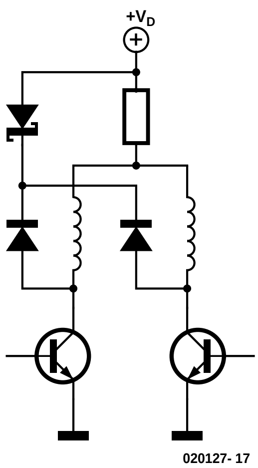

Figure 7. Series resistors used to limit the motor coil current.

out losing step.

Accuracy

This is defined as the difference between the theoretical and actual rotor position expressed as a percentage of the step angle. Typically this is approximately ±5% and this positioning error is non-cumulative.

Hysteresis Error

This is the maximum accumulated error from theoretical position for both forward and backward direction of rotation.

Resonance

A stepper motor responds to a series of input pulses, each pulse causing the rotor to advance one step. In this time the motor's rotor must accelerate and then decelerate to a stop. This causes ringing, overshoot and vibration. There are some speeds at which the motor will not run. This is called its resonant frequency. The objective is to design the system so that no resonant frequencies appear in the operating speed range. This problem can be eliminated by means of using mechanical dampers or external electronics.

Stepper motor driving

In next month's instalment, we'll discuss a practical design for a high-power 3-channel stepper motor driver. To be able to understand the operation of this circuit, some more theory is required, together with an explanation of what the various terms mean. We'll take it step by step.
The stepper motor driver circuit has two major tasks:

1. To change the direction of magnetic flux in the phase by controlling the current direction and/or path.
2. To control and limit the current magnitude through the windings, with as short current rise and fall times as possible to achieve the highest performance drive.

Flux Direction Control

To continually step the motor requires a change of the flux direction, independently in each phase. This change is done by changing the current direction, and may be done in two different ways, using a bipolar or unipolar drive.

Bipolar Drives

This refers to the principle where the flux direction in one phase is reversed by shifting the voltage polarity across the winding causing the current direction to reverse. As illustrated in **Figure 5**, this requires four switches per phase.

Unipolar Drives

This term refers to the principle where the flux direction in one phase is reversed by shifting the current from one half of the winding to the other half. This requires two switches per phase, see **Figure 6**.

Current Control

In order to limit the power dissipation in the winding resistance and control the torque, the current must be controlled. There are two main principles to limit the current: current-limited drive and chopper-drive. Both can be realized either as a bipolar or unipolar driver.

Current limiting

This method (**Figure 7**) basically utilizes a constant voltage supply with a series ('dropper') resistor used to limit the current. The disadvantage of this method is the power dissipation in the series resistor.

Bi-level L/R Drive

This method, illustrated in **Figure 8**, utilizes a secondary supply, connected to the winding during the initial current build-up period. After a preset period, as the current has reached its nominal value, this secondary supply is disconnected. The disadvantage of this method is the need of a second power supply.

Chopper Control

The chopper driver provides the optimal solution both to current control and fast current build-up. The basic idea (**Figure 9**) is to use a supply voltage, which is several times higher than the nominal voltage of the motor. The current rise rate, which initially is V/L, is allowed to increase substantially. By controlling the duty cycle of the chopper, an average voltage and an average current equal to the nominal motor voltage and current are created. Constant current regulation is achieved by utilizing a current sense resistor in series with the motor winding to provide feedback to limit the nominal current.

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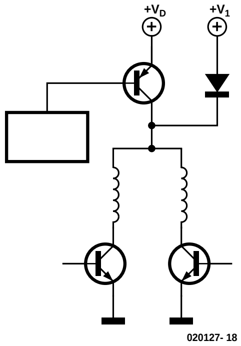

Figure 8. Bi-level current limiting.

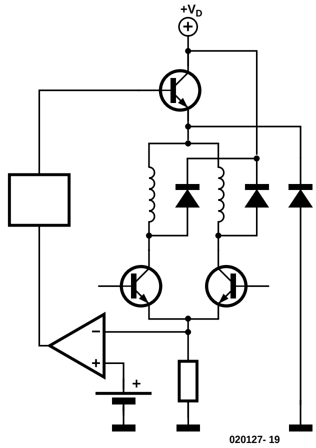

Figure 9. Principle of chopper control.

Next month

we'll discuss a high-power 3-channel stepper motor driver with PC control, complete with associated control software. The driver is PIC controlled and communicates with your PC through a serial link.

Driver Selection Chart

Drive Method	Component Cost / Count	Electrical Noise	Torque / Speed / Resolution	Power Efficiency	Design Notes	Application
1. Unipolar Constant Voltage	Low, 4 power transistors per motor.	Low	Holding torque depends on supply voltage and motor temperature. Large torque ripple when used in half-step mode.	Lowest output power. Low efficiency. Maximum power dissipation at standstill.	Driver transistors must be rated twice the supply. Power supply must be designed for given motor winding.	Low speed and low power. Normally used only with small motors.
2. Unipolar L/nR Constant Voltage	Low, 4 power transistors per motor.	Low	Holding torque depends on supply voltage and motor temperature. Large torque ripple when used in half-step mode.	Very low efficiency. Maximum power dissipation at standstill increased by L/nR ratio.	Problems with heat dissipation from the series resistors.	Low/medium speed and low power.
3. Unipolar Timed bi-level	Medium, 6 power transistors per motor. Requires CPU or timing circuit.	Medium	Holding torque depends on supply voltage and motor temperature.	Medium efficiency.	If bi-level voltage ratio is high, controlling of the holding torque & step accuracy is made difficult.	Low/medium speed and low/medium power.
4. Unipolar Constant Current	Medium / high, 6 power transistors per motor.	Medium / High	Optimum torque at high speeds. 70% optimum torque at low speeds. No torque ripple when used in half-step mode.	Medium / high efficiency	Driver transistors must be rated twice the supply. Winding leakage inductance has to be considered when designing snubber circuit.	High speed and medium power.
5. Bipolar Constant Current	High, 8 power transistors per motor. Integrated drivers available for low-medium power applications.	High	Optimum torque at both low and high speeds.	High efficiency. Maximum O/P power. Power loss in current sense resistors.	Problems with noise and interference may occur.	High speed and high power.
6. Bipolar Constant Current Micro-stepping	Very High, 8 power transistors per motor. Current control electronics more costly. Integrated drivers available for low/medium power motors.	High	Optimum torque at both low and high speeds. Resonant free operation at low speeds. Increased resolution.	High efficiency. Maximum output power. Power loss in current sense resistors.	Problems with noise and interference may occur.	High speed and high power. Used if a higher resolution or resonant free operation is required.