STEP MOTOR BASICS

MOTOR ELECTRICAL BASICS

A step motor is a constant output power transducer, where power is defined as torque multiplied by speed. This means motor torque is the inverse of motor speed. To help understand why a step motor's power is independent of speed, we need to construct (figuratively) an ideal step motor.

An ideal step motor would have zero mechanical friction, its torque would be proportional to ampere-turns and its only electrical characteristic would be inductance. Ampere-turns simply mean that torque is proportional to the number of turns of wire in the motor's stator multiplied by the current passing through those turns of wire.

Anytime there are turns of wire surrounding a magnetic material such as the iron in the motor's stator, it will have an electrical property called inductance. Inductance describes the energy stored in a magnetic field anytime current passes through this coil of wire.

 Inductance (L) has a property called inductive reactance, which for the purposes of this discussion may be thought of as a resistance proportional to frequency and therefore motor speed.

According to ohm's law, current is equal to voltage divided by resistance. In this case we substitute inductive reactance for resistance in ohm's law and conclude motor current is the inverse of motor speed.
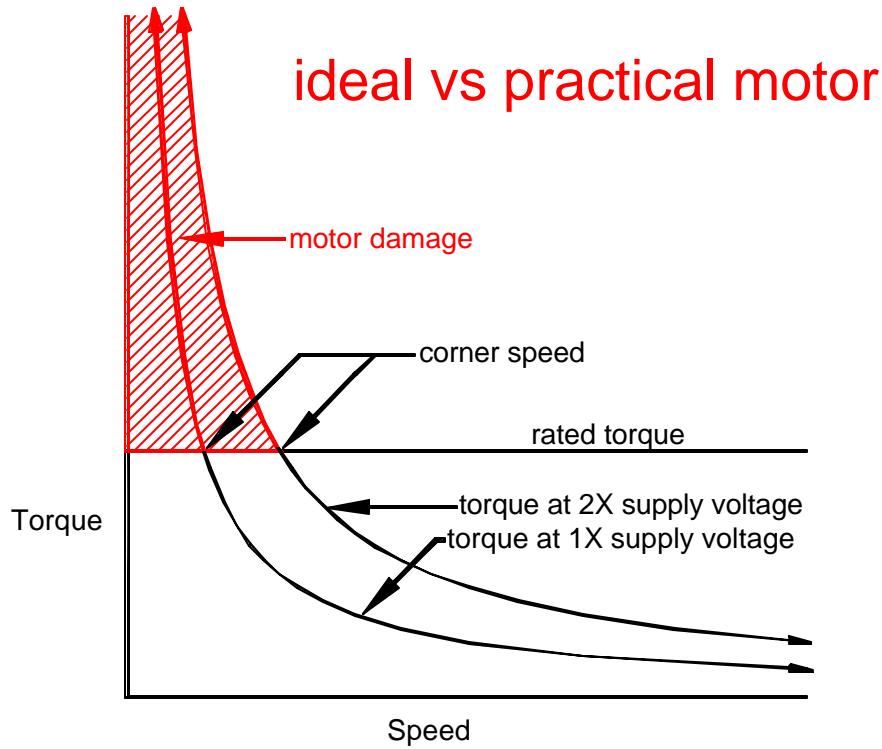
Since torque is proportional to ampere-turns (current times the number of turns of wire in the winding), and current is the inverse of speed, torque also has to be the inverse of speed.

In an ideal step motor, as speed approaches zero, its torque would approach infinity while at infinite speed torque would be zero. Because current is proportional to torque, motor current would be infinite at zero speed as well.
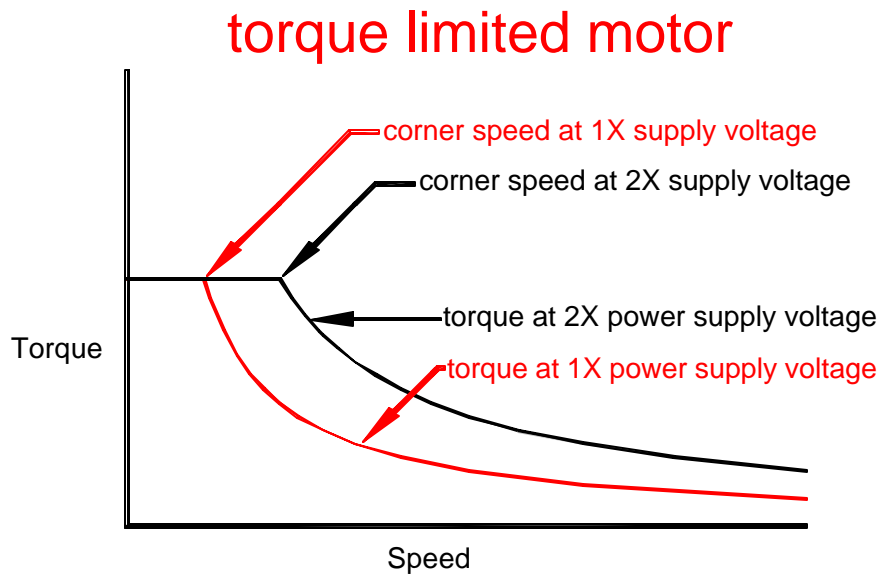
Electrically, a real motor differs from an ideal one primarily by having a non-zero winding resistance. Also the iron in the motor is subject to magnetic saturation, as well as having eddy current and hysteresis losses. Magnetic saturation sets a limit on current to torque proportionality while eddy current and hysteresis (iron losses) along with winding resistance (copper losses) cause motor heating.

SPEED-TORQUE CURVE BASICS

In the previous section it was shown that motor torque varies inversely with speed. This then is the motor's natural speed-torque curve. Below a certain speed, called the corner speed, current would rise above the motor's rated current, ultimately to destructive levels as the motor's speed is reduced further. **Fig. 1**

ideal vs practical motor

motor damage

corner speed

rated torque

torque at 2X supply voltage
torque at 1X supply voltage

Torque

Speed

To prevent this, the drive must be set to limit the motor current to its rated value. Because torque is proportional to current, motor torque is constant from zero speed to the corner speed. Above the corner speed, motor current is limited by the motor's inductive reactance.

torque limited motor

corner speed at 1X supply voltage
corner speed at 2X supply voltage

torque at 2X power supply voltage
torque at 1X power supply voltage

Torque

Speed

The result now is a two-part speed-torque curve which features constant torque from zero speed until it intersects the motor's natural load line, called the corner speed, beyond which the motor is in the constant power region.

A real step motor has losses that modify the ideal speed-torque curve. The most important effect is the contribution of detent torque. Detent torque is usually specified in the motor data sheet. It is always a loss when the motor is turning and the power consumed to overcome it is proportional to speed. In other words, the faster the motor turns the greater the detent torque contributes power loss at the motor's output shaft. This power loss is proportional to speed and must be subtracted from the ideal, flat output power curve past the corner speed. This now constitutes a practical speed-torque curve. **Fig. 14**

ideal vs. practical curves

Torque
Power

ideal power output

actual power output

ideal torque

actual torque
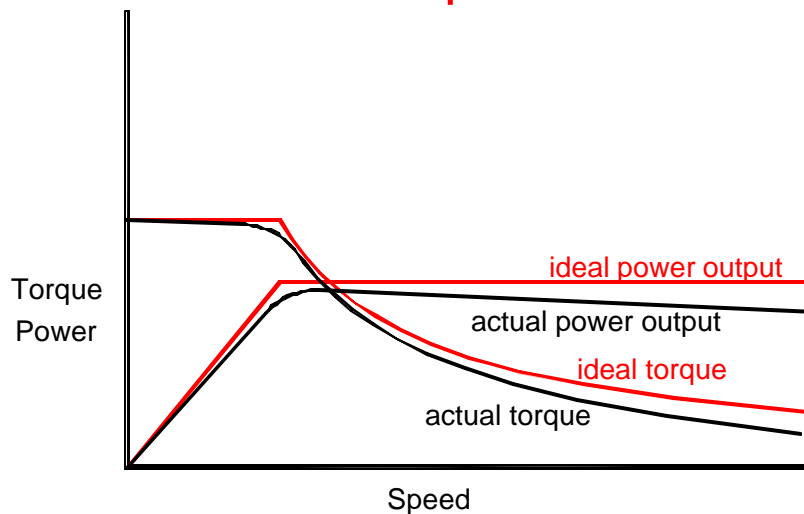
Speed

Notice how power output decreases with speed because of the constant-torque loss due to detent torque and other losses. The same effect causes a slight decrease in torque with speed in the constant torque region as well. Finally, there is a rounding of the torque curve at the corner speed because the drive gradually transitions from being a current source to being a voltage source. The drive limits current to the motor below the corner speed and thus is a current source. Above the corner speed, the motor's inductive reactance limits current and the drive becomes a voltage source as it applies all of the power supply voltage to the motor.

MID-BAND INSTABILITY

A step motor is highly resonant because it is a mass-spring system. The "mass" portion is the rotor and load moment of inertia while the "spring" portion is restoring torque of the magnetic field that drags the rotor along. Because of this velocity lags torque by 90 degrees.

The drive is a current source in the constant torque region and adds no additional phase lag. In the constant power region however the drive is a voltage source, so it introduces an additional 90-degree phase lag. The total phase lag now approaches 180 degrees, which is a setup for sustained, and building motor oscillation. This oscillation is commonly called mid-band instability or mid-band resonance.

The drive remedies this instability by adding a second-order, or viscous damping. This damping decreases the total phase lag so the motor cannot sustain oscillation, much in the same way shock absorbers damp the mass-spring suspension of a vehicle.

The figure below shows the effect of uncompensated mid-band resonance. Though it is possible to accelerate through the resonant region, it is not possible to operate the motor continuously in that speed band. This is because the oscillation that causes the motor to stall takes from half a second to 10 seconds to build to an amplitude sufficient to stall the motor.

mid-band resonance

Torque

with viscous damping

without viscous damping
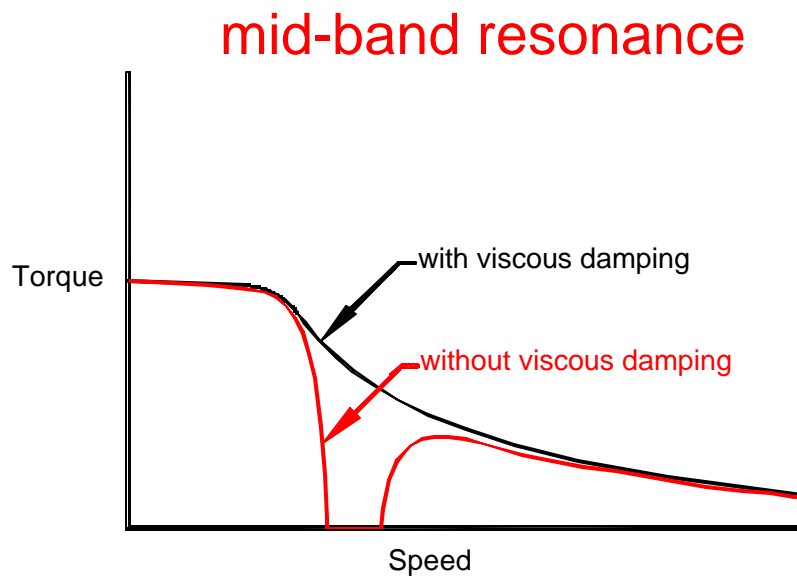
Speed

MOTOR POWER BASICS

 The motor power output (speed times torque) is determined by the power supply voltage and the motor's inductance. The motor's output power is proportional to the power supply voltage divided by the square root of the motor inductance.

If one changes the power supply voltage, then a new family of speed-torque curves result. As an example, if the power supply voltage is doubled then a new curve is generated; the curve now has twice the torque at any given speed in region 2. Since power equals torque times speed, the motor now generates twice as much power as well. **Fig. 15**
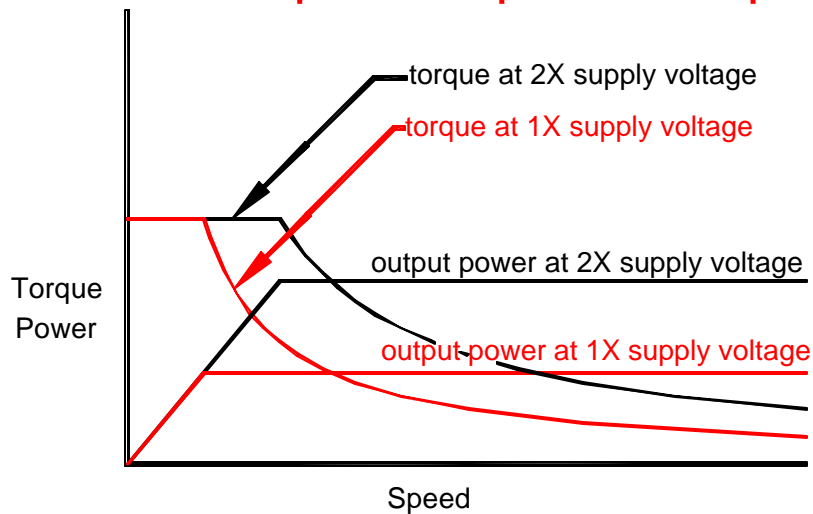
The following graph shows the effect of rewiring the motor from full-winding to half-winding while keeping the same power supply voltage.
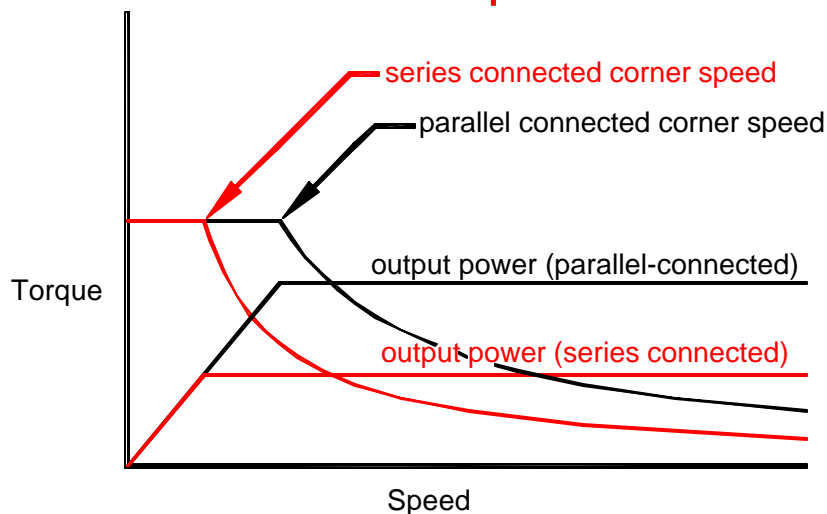

This shows a half winding connected motor delivers twice as much power as a full winding connection at a given power supply voltage. This is because full-winding inductance is four times higher than the half-winding inductance.

Also note from the previous graph that motor output power doubles when the power supply voltage is doubled for either series or parallel-wired motors. Notice that a parallel-connected motor delivers performance identical to a series-connected motor running at twice the power supply voltage.

The next figure shows the effect of setting the motor current to twice the rated value. This abuses the motor because it will dissipate 4 times as much heat as setting the current to its proper value. The actual increase in low-speed torque is considerably less than double because magnetic saturation of the motor iron.

rated vs. 2X rated current
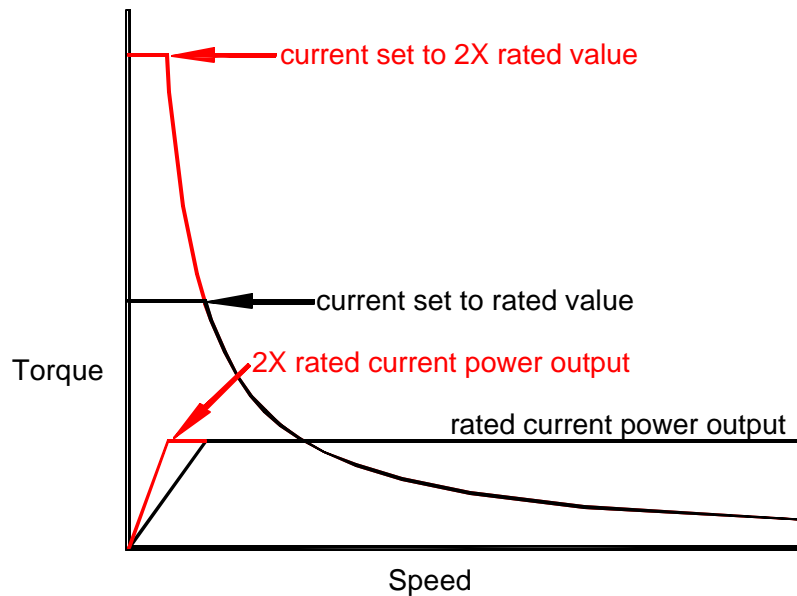
What can be seen is there is no increase of power output; the motor simply reaches its maximum power at a lower speed, all at the great expense of a four-fold increase in motor heating.

It is recommended the motor current always be set at the rated value also to get the best microstep smoothness. Setting the current higher degrades the linearity of motor and causes microstep bunching and attendant low-speed vibration.

What comes with increased motor power with increased power supply voltage is increased motor heating; this heating increases more rapidly than output power and ultimately sets the maximum output power from the motor. That is to say, the limiting factor in how much power a motor can deliver is ultimately determined by how much heat it can safely dissipate.

MOTOR CONNECTIONS

Step motors have either 4, 6 or 8 wires.

Four-wire motors are the simplest to connect and offer no connection options. Simply connect one winding to terminals 3 and 4, connect the other winding to terminals 5 and 6. If you don't know which two pair of wires are which, simply use an ohmmeter to check for continuity. The first two wires that have continuity connect to terminals 3 and 4, the remaining two wires go to terminals 5 and 6. If the motor turns opposite to the desired direction, exchange the wires going to terminals 3 and 4. **Fig. 4**

4-wire motor connection
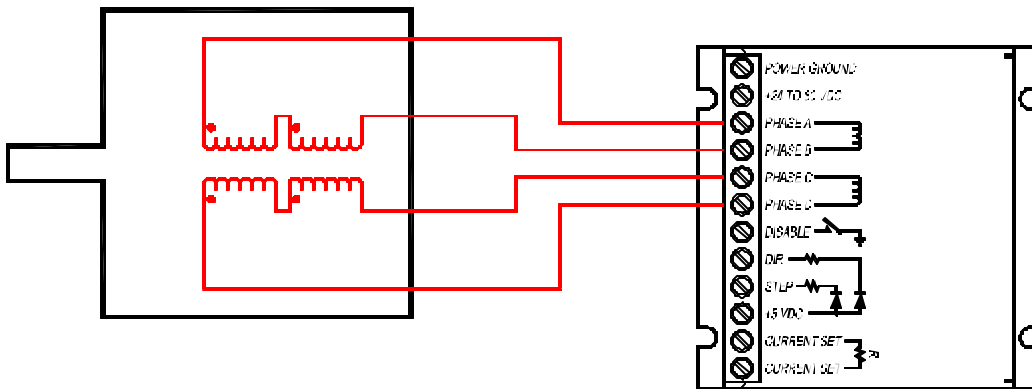
Six-wire motors are the most common. There are two connection options; full-winding and half-winding. A six wire motor is just like a four wire motor except there is a center tap on each of the two windings, for a total of six wires. For a half-winding connection, the center tap and one of the end wires are used.
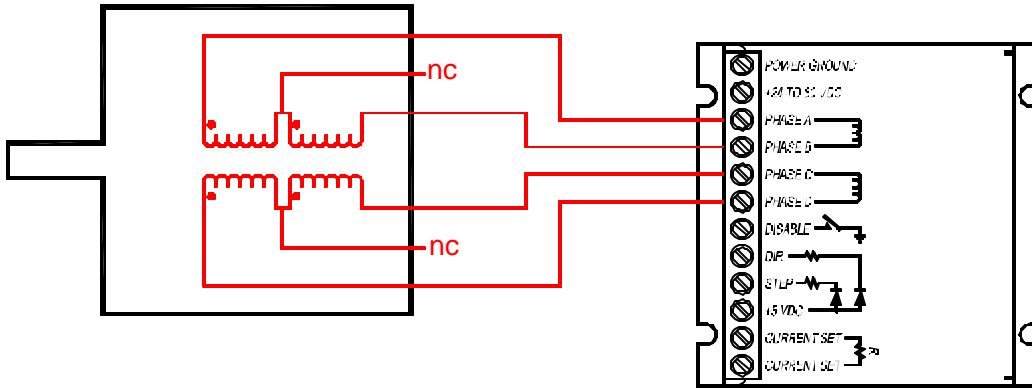
6-wire motor, half-winding connected
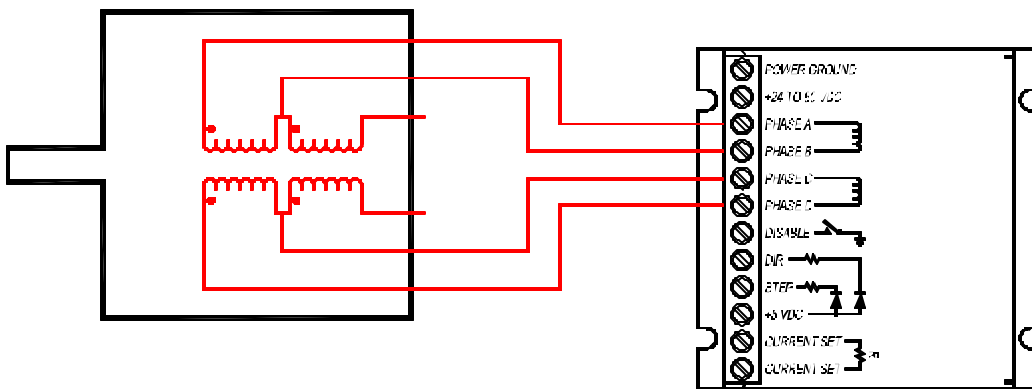
For a full-winding connection, the center tap is ignored and both end wires are used. The term "full-winding" is exactly equivalent to "series" connected while "half-winding" is virtually identical to "parallel" connected. The choice between the two is application dependent, which is discussed
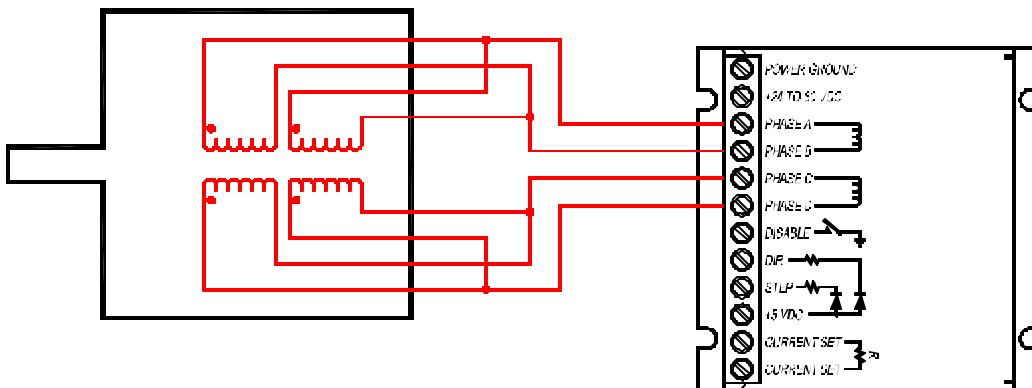
later; just remember to set the drive current to exactly half of the motor's rated unipolar current rating. **Fig. 5**
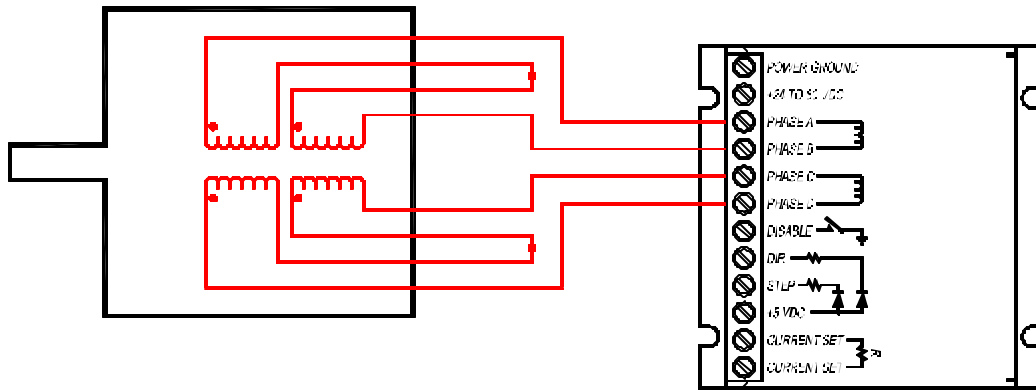
6-wire motor, full-winding connected

Eight-wire motors are about 3% more efficient when parallel connected than an equivalent half-winding connected six-wire motor, but are considerably more complicated to hook up. There is no advantage when comparing a series connection to a full-winding connection. As in a six-wire motor, the choice between series versus parallel connection is application dependent. Remember to set the drive current to exactly half of the motor's rated parallel current rating when using the series connection. **Fig. 6**

# 8-wire motor, parallel connected

8-wire motor, series connected

POWER GROUND
4.84 TO 80 VDC
PHASE A
PHASE B
PHASE C
PHASE D
DISABLE
DIR
STEP
(5 VDC
CURRENT SET
CURRENT SET

POWER SUPPLIES

The choice of a power supply is determined by voltage, current and power supply type, i.e. switcher versus linear regulated versus unregulated and purchased versus in-house designed. By far the most problematic factor is voltage, so we will leave it until last.

The easiest factor in choosing a power supply is its current rating. The current rating of the supply is based on your motor choice. The drive will always draw less than 2/3 of the motor's rated current when it is parallel (or half-winding) connected and 1/3 of the motor's rated current when it is series (or full-winding) connected. That is to say, a 6 Amp / phase motor will require a 4 Amp rated supply when parallel connected and a 2 Amp rated supply when series connected. If multiple motors and drives are used, add the current requirements of each to arrive at the total power supply current rating.

power distribution (star)
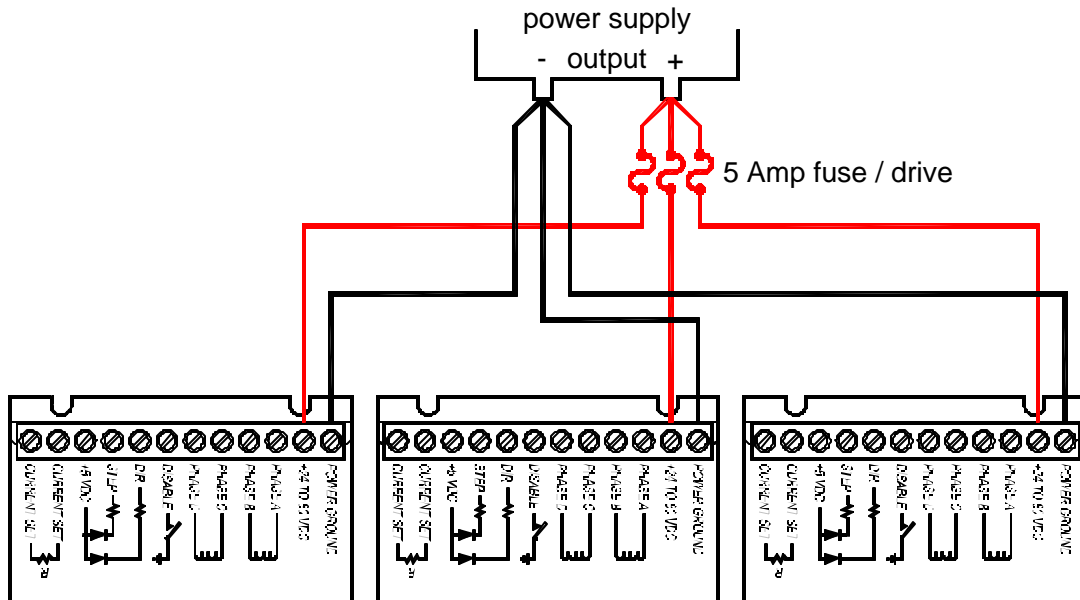
When using multiple drives from a common power supply, use individual supply and ground wires to each drive and return them to a common point back at the power supply. This is called a "star" power supply distribution; never ever use a "daisy-chain" power distribution, where the supply and ground wires for the next drive are picked up from the previous one.

It is good practice to use a fuse, (5 Amp, fast blow) for each drive. This way if a fault develops such as a short to ground, windings shorted, etc. the fuse will blow and protect the drive and power supply. It is cheap insurance.

If the cable run from the power supply to the drive exceeds 18" or if a fuse is used, place a 470uF 100 VDC capacitor across each drive's power terminals 1 and 2. Make sure the capacitor's "+" lead goes to terminal 2 and that its "-" lead goes to terminal 1. The capacitor is necessary because the drive draws power supply current in 20 kHz pulses and needs "flywheel" to work properly.

local capacitor

to power supply ground

470 uF
100 V   − +

POWER GROUND
)24 TO 80 VDC
PHASE A
PHASE B
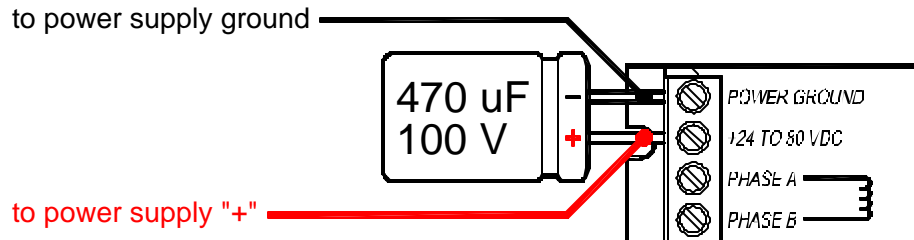
to power supply "+"

The power supply voltage must be between 24 VDC and 80 VDC. Beyond that, the choice of voltage is dependent on the application and the motor used. The power supply voltage should be between 3 to 25 times the motor's rated voltage. If it is less than 3 times, the drive may not operate smoothly and motor heating is excessive if it is more than 25 times the motor's voltage.

As an example, if a 3.8 Amp, 1.2 Volt half-winding connected motor is to be used, the power supply voltage should be between 24 and 30 VDC. If the same motor is full-winding connected, then it may be thought of as a 1.9 Amp, 2.4 Volt motor instead and the power supply voltage can be between 24 to 60 VDC. If the motor's voltage is not listed, then the resistance usually is. Simply multiply the rated current by the rated resistance to arrive at the motor's voltage.

The drive works best with unregulated power supplies though regulated linear and switching power supplies may also be used. What matters is the power supply must have a large output capacitor and an unregulated supply intrinsically has one.

If a linear regulated or a switching supply is to be used, then a large capacitor should be placed across the output terminals. A 2,000 to 10,000 uF capacitor should do.

If the choice is to make your own power supply then three components are needed; a transformer, a bridge rectifier and a filter capacitor. The transformer's current rating must be sufficient to run the motor. The DC output voltage of the supply will be 1.4 times the transformer's AC voltage rating of the secondary. For example, a 24 VAC secondary will provide about 34 VDC at the output of the supply. The bridge rectifier's voltage and current ratings must exceed what the supply will deliver. Finally the minimum filter capacitor size must be calculated. Use the following equation to do this:

$$C = (80,000 * I) / V$$

The results will be in microfarads for the capacitor if the value for "I" is amperes of current needed and "V" is the output voltage of the supply. When picking the capacitor, any value equal or greater will do for the capacitor size. Be sure to use a capacitor with a voltage rating at least 20 percent higher than the output voltage of the power supply. A sample 5 Amp, 68 VDC power supply is shown on the following page.

unregulated power supply

VAC

$$C = \frac{80,000 \times I}{V}$$
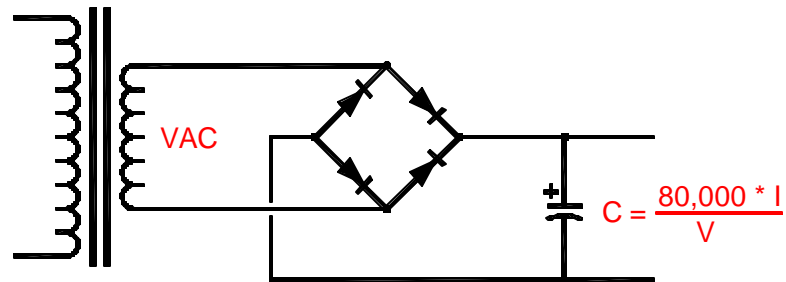
EXAMPLE: 68 VDC, 5 Amps   I = current
             48 VAC * 1.4 = 68 VDC   V = output voltage
             C = 5 * 80,000 / 68 = 5,882 uF   C = microfarads

There is a special consideration if the power supply voltage will be at or near the maximum voltage rating of the drive. If the motor will be rapidly decelerating a large inertial load from a high speed, care has to be taken to absorb the returned energy. The energy stored in the momentum of the load must be removed during deceleration and be safely dissipated. Because of its efficiency, the drive has no means of dissipating this energy so it returns it to the power supply. In effect, instead of drawing current from the power supply, the drive becomes a source of current itself. This current then may charge the power supply capacitor to destructive voltage levels.

If more than one drive is operating from the power supply this is not a problem since the other drive will absorb this current for its needs, unless of course it is decelerating as well. For this case or for a single drive it may be necessary to place a voltage clamp across the power supply in the form of a zener diode. The voltage of this diode must be greater than the maximum expected power supply voltage, yet low enough to protect the drive. A good choice would be either 82 volts or 91 volts as standard values.

MOTOR HEATING AND POWER SUPPLY VOLTAGE

There are two major causes of motor heating; copper losses and iron losses. Copper losses are the easiest to understand; this is the heat generated by current passing through a resistance, as in the current passing through the motor's winding resistance. Often this referred to as " I squared R" dissipation. This cause of motor heating is at a maximum when the motor is stopped and rapidly diminishes as the motor speeds up since the inductive current is inversely proportional to speed.

Eddy current and hysteresis heating are collectively called iron losses. The former induces currents in the iron of the motor while the latter is caused by the re-alignment of the magnetic domains in the iron. You can think of this as a "friction heating" as the magnetic dipoles in the iron switch back and forth. Either way, both cause bulk heating of the motor. Iron losses are a function of AC current and therefore the power supply voltage.

As shown earlier, motor output power is proportional to power supply voltage, doubling the voltage doubles the output power. However, iron losses outpace motor power by increasing non-linearly with increasing power supply voltage. Eventually the point is reached where the iron losses are so great that the motor cannot dissipate the heat generated. In a way this is natures' way of keeping someone from getting 500 hp from a size 23 motor by using a 10,000 volt power supply.

At this point it is important to introduce the concept of overdrive ratio. This is the ratio between the power supply voltage and the motor's rated voltage. An empirically derived maximum is 25:1. That is to say, the power supply voltage should never exceed 25 times the motor's rated voltage. Below is a graph of measured iron losses for a 4 Amp, 3 Volt motor. Notice how the iron losses range from insignificant to being the major cause of heating in the motor compared to a constant 12 Watt copper loss (4 Amps times 3 Volts).

iron losses vs. power supply voltage
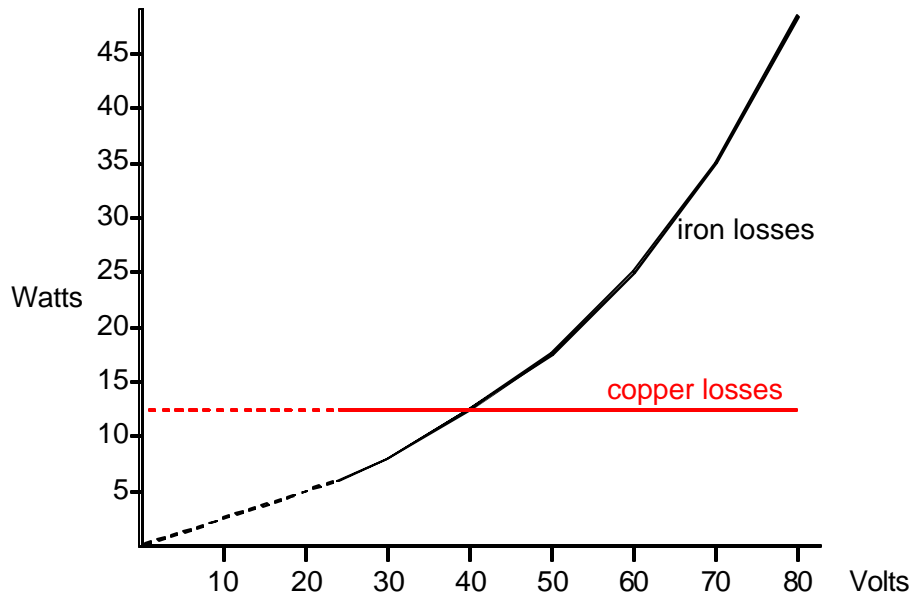
ACCURACY AND RESOLUTION

Step motors by and large are used in open loop positioning and velocity applications. There is no feed-back transducer to set the ultimate accuracy of the system. Consequently it falls on the motor and the drive's precision and behavior to determine the accuracy of the application.

Through micro-stepping, 2nd order damping and precision sine / cosine current references, the drive has cured the step motor of its inherent vices to make it a viable candidate for precision motion control applications. Neglecting the drive, the motor still has characteristics that must be considered in regards to ultimate accuracy in any application.

A step motor is a mechanical device that is manufactured to a certain tolerance. Typically a standard motor has a tolerance of +/- 5% non-accumulative error regarding the location of any given step. This means that any step on a typical 200 step per revolution motor will be within an .18-degree error range. Stated otherwise, the motor can accurately resolve 2000 radial locations. Coincidentally this is the resolution of a 10 microstep drive.

Any microstep resolution beyond 10, such as 125, yields no additional accuracy, only empty resolution. By analogy, a voltmeter having a 6 digit display while having a 1% accuracy would have meaningful information only in the first two digits. There are two exceptions justifying higher resolutions; the step motor is being run in a closed-loop application with a high-resolution encoder or the application requires smooth operation at very low speeds (below 5 full steps per second).

Another factor affecting accuracy is motor linearity. Motor linearity refers to how the motor behaves between its ordinal step locations. Ideally a 1.8 degree per step motor should move exactly 0.18 degrees for every step pulse sent to a 10 microstep drive. In reality all step motors exhibit some non-linearity, meaning the microsteps bunch together rather than being spread evenly over the span of a full step. This has two effects; statically the motor position is not optimum and dynamically low speed resonances occur because of the cyclic acceleration where the microsteps are spread apart and deceleration where they bunch up. The figures below show a motor with terrible linearity and a motor with excellent linearity.

bad vs. good motor linearity
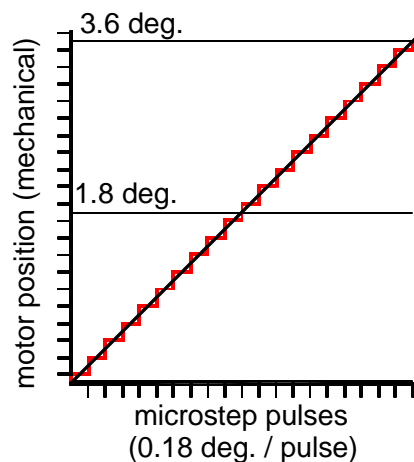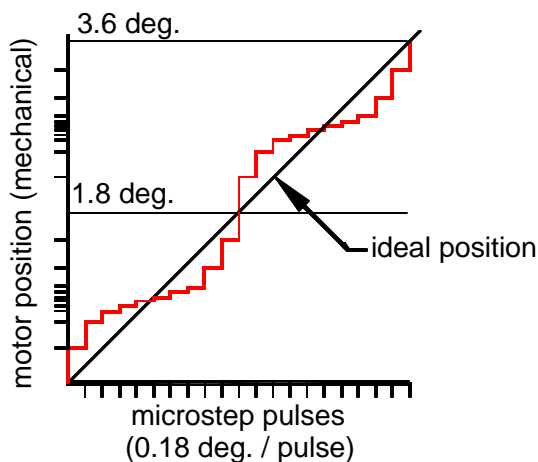
Finally, the static or frictional load applied to the motor affects accuracy. A stopped step motor, which has 100 oz/in of holding torque, is fundamentally different than a brake that has the same holding torque.

The brake will not turn at all until its holding torque is exceed. However a step motor only generates restoring torque if it is displaced from its rest position. Using the brake analogy, think of the output shaft being connected to the break with a torsional spring. Now when applying a load, the output shaft has to be radialy displaced to apply torque to the break.

When torque sufficient to overcome the holding torque is applied to a step motor, the shaft will jump to the next stable location, which is 4 full steps ahead or behind the original one, depending on which direction the load is applied. Peak restoring torque occurs a full step ahead or behind the original location, beyond which it weakens and reverses at the 2 full step position to attract the shaft to a 4 full step location ahead or behind the original one.

The relationship between restoring torque and shaft error angle is approximately sinusoidal as shown below.
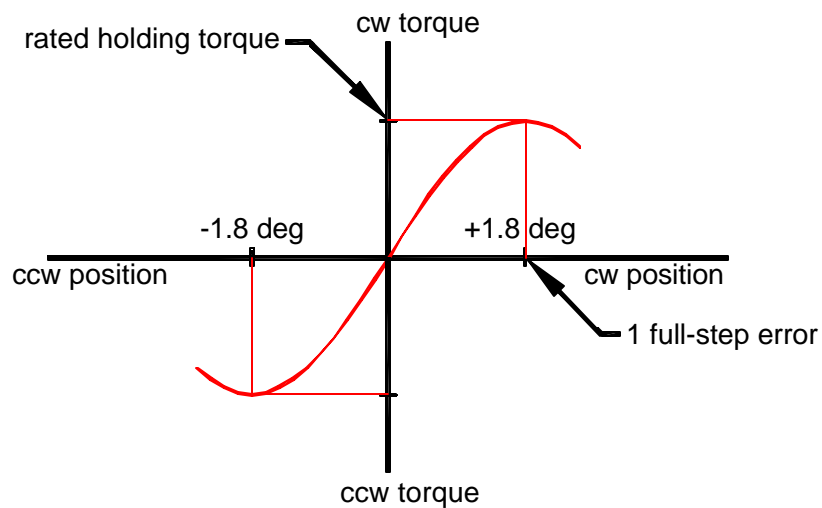
From this one may approximate that a static torque load equal to 15 percent of the holding torque will displace the motor shaft 1/10 of a full step about the origin.

CHOOSING A STEP MOTOR AND POWER SUPPLY VOLTAGE

The choice of a step motor and power supply voltage is entirely application dependent. Ideally the motor should deliver sufficient torque at the highest speed the application requires and no more.

Any torque capability in excess of what the application requires comes at the high cost of unnecessary motor heating. Excess torque capability beyond a reasonable safety margin will never be used but will exact the penalty of an oversize power supply, drive stress and motor temperature.

Learn to distinguish the difference between torque and power. High initial torque at low speed does not mean efficient motor utilization. Usually power is the more important. Bias the motor's operating point through power transmission gearing to operate the motor at its maximum power; normally just past its corner frequency.

The maximum shaft power obtainable with the drive is around 250 Watts, or 1/3 of a horsepower. This is primarily achieved with double and triple stacked size 34 motors.

Size 23 motors are physically to small to dissipate the resultant heat and size 42 motors are to big to be properly impedance matched; if their rated current is less than the 7 Amp limit of the drive, then the optimum overdrive voltage is beyond the 80 Volt limit. If the rated voltage is less than 1/25 of 80 Volts, then the phase current will probably exceed 7 Amps.

Also the detent torque on a size 42 motor is significantly higher than in smaller motors. This detent torque is always a loss that must be subtracted from the potential available power output of the motor; in other words its output power drops more rapidly with speed than smaller motors. Use size 42 motors only if high torque is required at low speed and it is not practical to gear down a smaller motor.

An efficient motor, defined as the smallest motor sufficient to meet the demands of the application, will run hot. Think of the motor as having a fixed power conversion efficiency. Some percentage of the input power will be converted to heat; the rest will be converted to mechanical power. To get the maximum performance from the motor, the waste heat must be just under what the motor can tolerate. Usually this motor will be biased to operate just past the corner speed as well.

The place to start is to determine the load torque in oz/in. Be sure to include the torque necessary to accelerate the load. Next come up with the maximum speed the application has to operate at in full steps per second. Multiply the two together and then divide the result by 4506 to calculate the power in watts necessary to meet the application requirements. Pick a motor at a power supply voltage that provides a 40 percent reserve power margin above your requirements

G201 CONTROL INTERFACE

The G201's control interface consists of the "Disable" input, the "Step, Direction and +5 VDC" and "Current Set" inputs.

DISABLE INPUT:

The "Disable" input shuts-off the motor by turning off all eight power transistors. All switching activity stops on the motor leads and the motor power drops to zero. Short the "Disable" input (term. 7) to auxiliary ground (term. 12) to disable the motor.

The purpose of the "Disable" input is for applications where it is necessary the motor generate no electrical interference when stopped, where it is necessary to free-wheel the motor, or as a means of power management. It is a very effective way of reducing motor heating in applications where there is assurance the motor cannot be back-driven while disabled. If system friction is greater than the motor detent torque, then motor will not move at all from its "on" position when disabled.

Be careful. The drive stays on and will continue to totalize any step pulses sent to it. If more than 20 pulses are sent in either direction while the motor is disabled, it will lose its position once it is enabled again.

STEP, DIRECTION AND +5 VDC INPUTS:

The "Step" input (term. 9) and the "Direction" input (term. 8) are optically isolated from the G201's circuitry. The isolator diodes are connected common-anode and brought out to the "+5 VDC" input (term. 10). Each diode has a 200 ohm resistor in series and a 1K resistor in parallel with it.

The "Step" and "Direction" inputs are designed to interface with current-sink drivers such as standard TTL logic or open-collector transistors, which sink to ground. As a result the isolator common (+ 5VDC) must be returned to the controller +5 VDC supply to complete the circuit.

If controller voltage is higher, such as 12 VDC or 24 VDC, use a series resistor in line with the "Step" an "Direction" inputs to limit the current to 16 Ma. Recommended resistor values are 470 ohms for 12 VDC and 1.2K for 24 VDC controllers. Place the resistors at the drive end.

The drivers must be able to sink 16 mA (logic "0"). The driver output voltage must be at least 4.5 V (logic "1") and less than 0.5 V (logic "0") when driving the inputs. Switching time must be less than 100 nS.

Do not ever bundle the control interface lines together with the motor or power supply cabling. Keep the two separate by at least 0.25 inches, otherwise the motor leads will induce "noise" in the form of false extra step pulses in the "Step" input line. The result will be inaccurate positioning and erratic operation of the drive. If the cable from the controller to the G201 is longer than 36", consider using a shielded cable for the "Step", "Direction" and "+5 VDC" lines. Ground the shield at one end only; preferably at the controller end. Do not ground the other end of the shield.

Microstepping occurs on the falling edge ("1" to "0" transition) of the "Step" input, and is delayed from 4 to 60 uS depending on the motor's speed. To avoid missed or wrong-direction microsteps, change the "Direction" input simultaneously with the falling edge of the "Step" input or wait at least 75 uS after its passage before changing direction.

The maximum "Step" input frequency is 200 kHz. The minimum logic "0" time is 0.5 uS and the minimum logic "1" time is 4.5 uS. There are of course, no maximum times for either. The "Step" and "Direction" timing diagrams are shown in the following figure:

step and direction timing
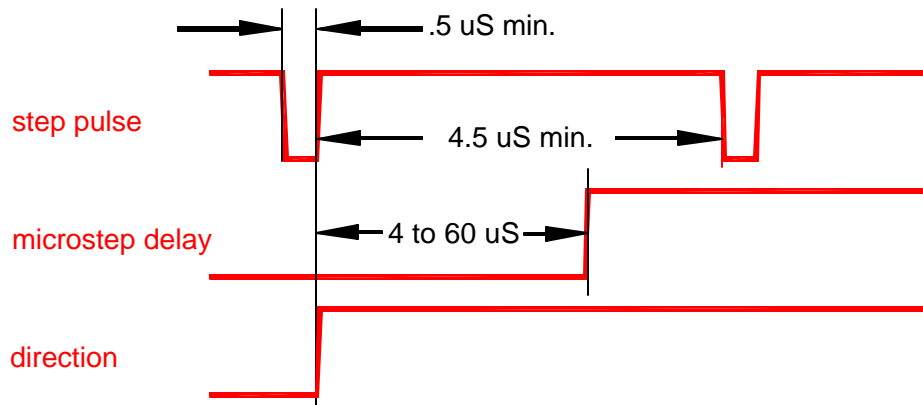
The "Current Set" inputs (term. 11 and 12) programs the G201's operating current for the motor. The maximum current is 7 Amps and the minimum current is 1 Amp.

Terminal 11 is the actual "Current Set" input while terminal 12 is an auxiliary ground connection, the same as "Power Supply Ground" (term. 1). Never use terminal 12 as a power supply ground; it is not meant to take the current.

Use the values listed on the cover of the G201 or use the following equation to calculate a current set resistor:

$$R = (47,500 * I) / (7 - I)$$

Where "I" is a 6-wire motor name-plate rated unipolar current, (or for 8-wire motors, the parallel rated current) and "R" is the resistor value in ohms. Pick the closest standard 5% resistor value to the calculated one.

When using 6-wire motors in the full-winding connection or 8-wire motors in a series connection, use exactly half of the previous value for "I". Motor torque is proportional to ampere-turns, so in this configuration there are twice as many turns of wire the current passes through, so only half as much current is necessary to generate the same amount of holding torque.

It is important to set the current to the value the motor manufacturer recommends for best microstepping performance. Any current setting significantly above or below this value will result in "bunching" of the microstep placement. At best the consequence will be poor accuracy when stopped and low speed vibration when moving, at worst overheating and premature failure of the motor.