Transverse Magnet Flux AKA Hybrid Step Motor Driver Techniques

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The transverse flux permanent magnet motor – also known as a hybrid step motor or hybrid servo motor – has a wide range of performances, depending upon how you drive these motors, and whether you operate them in open loop or one of the many variants of closed loop methods you use. In this third installment we will cover some of the many ways to drive these motors, as well as how these choices affect the performance of these motors.

The early years of transverse flux motors saw these motors driven from a sinusoidal line voltage, often using a capacitor to phase shift the current into the second phase to set the direction of motion. Voltage drive from a constant voltage produces an almost constant speed of operation. These motors are just a high-pole-count synchronous motor. The high-pole-count feature reduces the output speed while also increasing the available torque for a given package size. The use of high-pole-count motors can eliminate the gearhead—or at least a stage or two in high-inertia applications, thus simplifying the mechanical design.

Replacing the AC line voltage driving the coils, with switches that control the phase and frequency of the current through the stator windings, transformed the use of these motors from a synchronous motor to a step motor. The earliest step patents show relays being used to control the flow of current through the windings. These were later replaced with transistors, and a growth of complexity which has continued to this day in extending the capabilities of these motors.

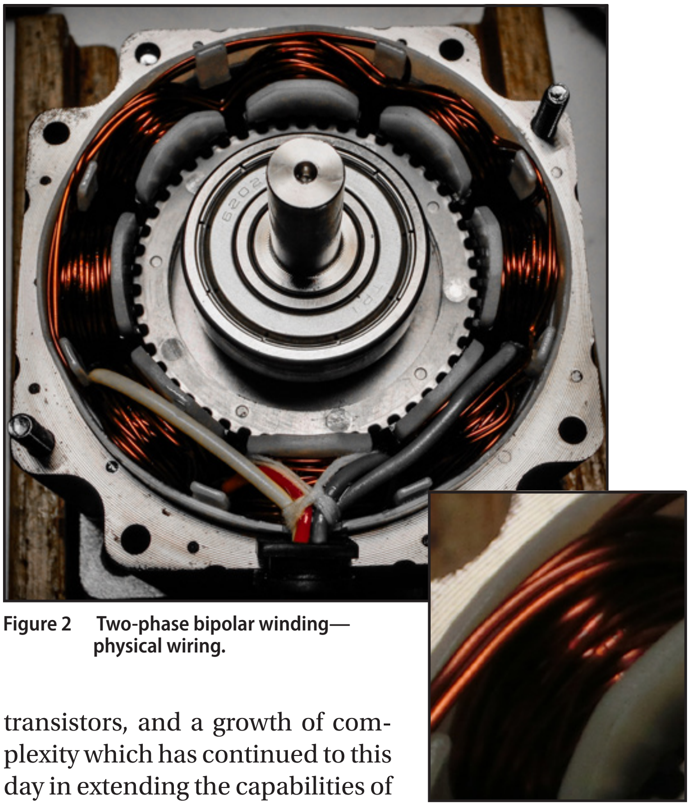

Figure 2 Two-phase bipolar winding—physical wiring.

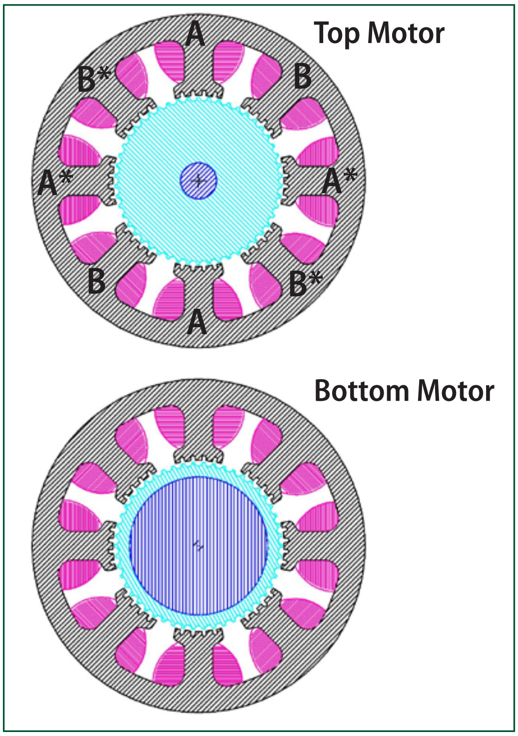

Figure 1 Motor windings, rotor teeth.

Motor Construction

Let us first look at the physical wiring of these motors and then how they are typically represented in schematics. The common 2-phase, 1.8-degree stepper normally has 8 pole pieces with 5 or 6 teeth each. A gap between the pole pieces provides space for wire to pass while winding the motor; the two windings function similarly. I will label the top pole piece in this view as A. Going clockwise, then other poles are B, A*, B*, A, B, A*, and B* (Fig. 1). The winding sense for A windings is opposite the sense for A* windings; likewise for the B and B* windings. For this position of the rotor, with respect to the stator, the teeth of the stator poles at "A" locations have maximum alignment with the upper rotor teeth, while the teeth of the stator at "A*" locations have minimum alignment with the upper rotor teeth and maximum alignment with the lower rotor teeth. A similar tooth alignment for "B" and "B*" stator "claws" is seen if the rotor is rotated by one full step or 1.8 degrees mechanical. Thus, if A is energized such that A claws are attracted to the teeth of top pole cap, the A* claws are simultaneously attracted to the teeth in the lower pole cap.

Although the actual design has 8 stator windings interconnected as two phases, the typical schematic shows the two winding (sets) at 90 (electrical) degrees from each other. The stators are typically wound with two smaller gauge wires wound simultaneously around each pole piece (claw), as the thinner wires are easier to handle, and they pack in better to give a higher copper fill (Fig. 2). The magnified view (Fig. 2 insert) shows the bifilar = two wire construction.

Some motors bring out all 8 connections (Fig. 3) to allow the user to wire them as they please. Other motors are sold with these internal coils either internally connected in parallel to provide a higher current winding, or in series for a lower current winding. A unipolar motor will commonly wire the coils of each phase in series and bring out the center tap, resulting in a 6-wire unipolar configuration. We will look at each of these and their various drive circuits.

Unipolar Drivers

There are a couple of major divisions in the driving of these motors: Unipolar and bipolar. With unipolar, the (intentional) driven signal through a given winding only flows in one direction. Two separate windings over the same magnetic structure are used, with the connection for the second winding reversed to allow reversing the magnetic flux polarity between using the first coil half and the second coil half. Bipolar drives have one "logical" winding-per-pole-piece. I say logical as most commercial step motors use a bifilar winding, i.e. — two wires wound side-by- side around the stator pole. The smaller-diameter wire is easier to wind, and the resulting motor can be used either for unipolar or bipolar operations, according to how the windings are interconnected. The two bifilar windings on each of the two phases results in a number of wiring configurations: 4-wire, which is a bipolar configuration; 6-wire, which supports unipolar drivers (although bipolar drivers can use 4 of the 6 connections and ignore the others); and 8-wire configurations, which allow the user to choose how the windings are interconnected.

The 6-wire unipolar design (Fig. 4) runs the motor from a supply voltage that is equal to the motor winding voltage rating. The current is automatically limited by the winding resistance of the motor. Energizing Q1 causes current to flow from V+ through the center tap to A and to ground. We will consider that this causes the shown north-south alignment of the rotor magnets. Alternatively, energizing Q2 (with Q1 off) reverses the direction of the magnetic field, causing the rotor to want to move to 180 (electrical) degrees from the orientation shown. D1 provides a path for the current flowing through the motor inductance to continue flowing when Q1 is turned off, limiting the inductive "kick" to protect the transistor. This circuit will work, but the motor speed will be severely limited. First, the current will only slowly decay when the transistor is turned off, as the voltage across the inductor will only be one diode drop. The rate of change of current though the winding is the voltage across the inductance divided by the inductance; the higher-voltage motors tend to have a large inductance. Second, the energizing Q1 will pull node "A" low, which will try to pull A* higher than V+, resulting in current flow through D2, which momentarily reduces the torque-producing magnetic flux.

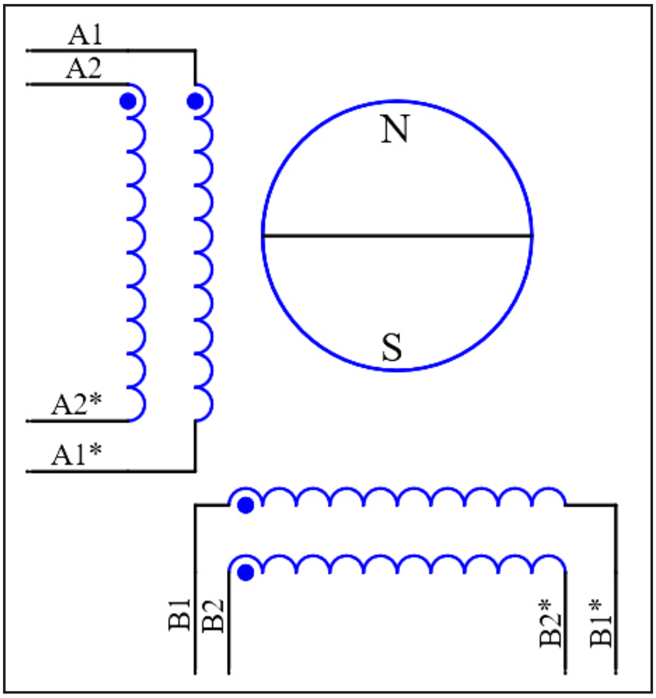

Figure 3 Eight-wire configuration.

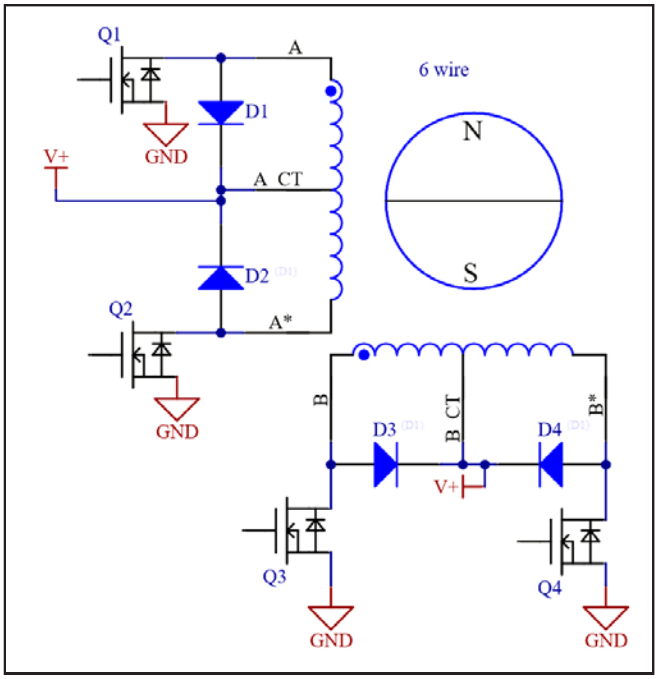

Figure 4 Six-wire unipolar.

Adding Zener diodes D5 and D6 (Fig. 5) — with a voltage rating greater than V+ — prevents the voltage induced at A* when A is energized from being high enough to overcome D2 and D5; thus the flux is not reduced at turn on. The current through the energized coil is also now able to decay quickly at turn-off, as the voltage generated by the field decay sees a higher voltage, i.e. — the D1 and D5 in the case of phase A.

This improvement can increase the speed capabilities of the motor by about a factor of 3 for the same motor and supply. The current rise is still limited by the relatively low V+ rating and comparatively large inductance of high-voltage, low-current motors. The time constant of the current for this configuration is t = L/R. The current must be kept low to prevent overheating of these motors, as the resistive loss of each winding is V+ times the current rating of the winding at that voltage.

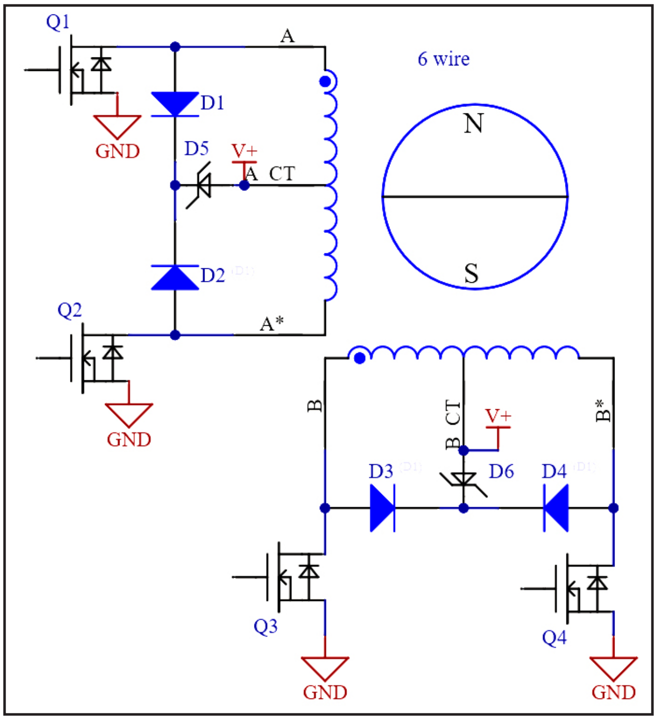

Figure 5 Faster decay unipolar.

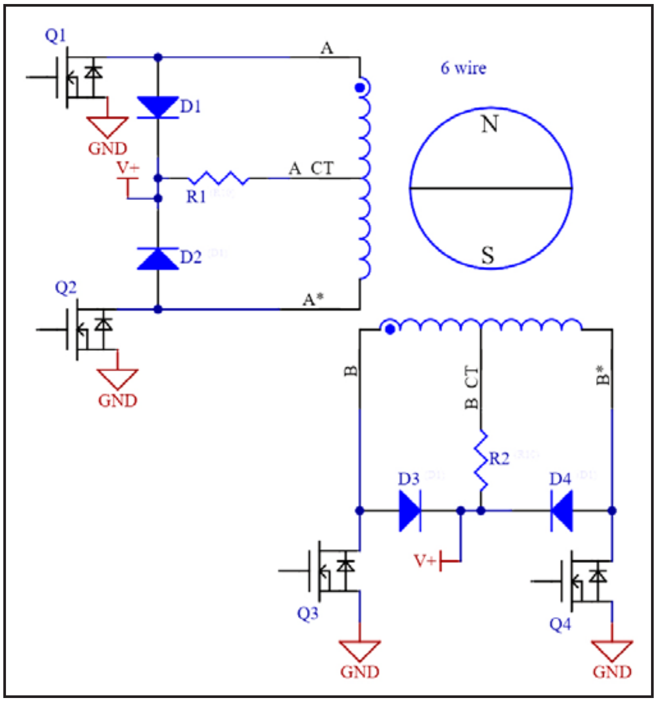

Figure 6 L/10R unipolar drive.

What is needed is a way to speed up the rise in current (and the fall in current) and to also allow the current to rise in the presence of a higher back-EMF present when the motor is spun faster.

This was accomplished (Fig. 6) by adding an external resistor in series with the center tap voltage. If the external resistance was 9 times the half-winding (A to A_CT) resistance, the result is a 10-fold increase in current rise and fall times. Any back-EMF now faces a significantly higher power supply voltage, allowing the motor to supply significantly more mechanical power at higher speeds. This can be done using either a lower-voltage motor winding, a higher supply voltage — or a combination of both; this was a common solution to many early CNC implementations. The resistors generate a significant amount of unwanted heat, but rapid motion at high torques is easily accommodated.

Bi-Level Unipolar Drivers

The next step along this full- and half-step methodology was to allow the resistor to be replaced by a switched high-voltage supply (Fig. 7); this is called *bi-level.* The high voltage is switched on just long enough for the current to reach the steady state current, and then the voltage is dropped down to the steady state voltage. For a 5v step motor rating, 50v may be applied for so many microseconds after a phase is turned on, and then the center tap voltage is dropped down to 5v. The catch diodes go to the higher voltage supply to allow for more rapid current decay when the phase is turned off.

For phase A, Q5 switches the V++ supply on to the center tap of A. Once a time has elapsed or (preferred) the current is sensed at the motor current rating, Q5 turns off and Q6 turns on, thus providing a supply path for the current to be sustained.

The unipolar drive can also be chopped to sustain current, but the rapid current decay can cause large ripple currents and increases losses (heating) in the motor. Most of the efforts with PWM drives have thus been developed with bipolar

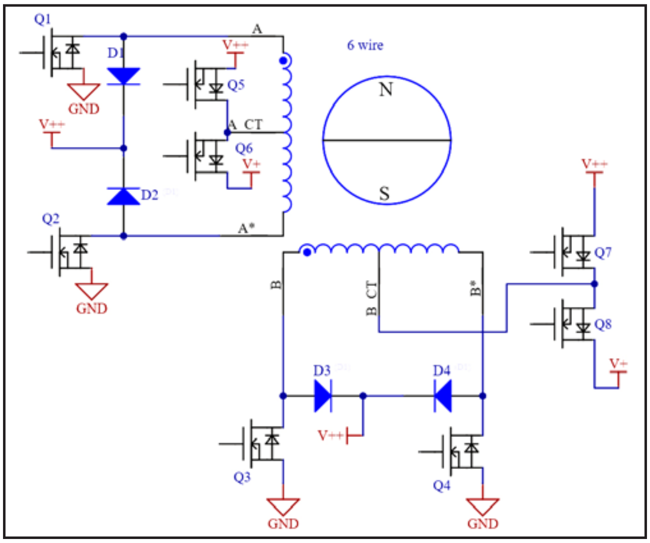

Figure 7 Bi-level unipolar drive.

motors, which will be detailed below.

Note that the unipolar drive does not need to operate fully switched; it alternately can be operated in analog fashion, where the winding current is monitored and the transistor (bipolar or MOSFET) modulated to produce the wanted current. US4121145 teaches a unipolar motor operating in microstepping mode where the net current for phase A is made to follow a sine wave, while that for phase B is made to follow a cosine. A lookup table feeding a DAC provides the sine and cosine voltage references to either an analog current controller or in other designs to a chopping drive to generate the wanted sine and cosine winding currents. Command step and direction pulses walk through the sine-cosine table. US4091316 takes this further using a tachometer on the shaft to add a damping term into the commanded current to implement damping in the system.

Bipolar Drives

Bipolar drives require twice as many active power devices as the simple unipolar techniques. The two windings in the bifilar windings are commonly wired in parallel to reduce the back-EMF and the inductance. This results in one-half the winding resistance versus the unipolar configuration. With resistive power losses P=I^2*R, for the same current the heating is one-half, or if the heating is maintained at the same level, the current can be increased by the square-root of two, which is a current increase of 41% with a similar torque improvement (if the motor magnetics are not saturating). This is a significant torque improvement now that active power devices have mostly been integrated and their cost has greatly reduced from the early days. Again, the schematics in this section are greatly simplified and do not show the transistor drive circuitry; bipolar transistors can be used instead of MOSFETS.

The same bipolar schematic (Fig. 8) can be used both in a full-step L/R configuration, as an L/10R by adding a resistor in series with each motor winding, or as a chopper drive if a current sensor is added to sense each winding current (Fig. 9).

The simple L/R bipolar driver keeps Q1 and Q4 in the same state, and opposite to Q2 and Q3. That is, the winding is either energized A to A*, or alternatively A* to A; phase B functions similarly. This drive operates similarly to the faster-decay unipolar drive in capability—except that the motor current can be 41% higher with the same motor heating—so the motor puts out more torque. The motor is also able to dynamically brake easily as the energy from the motor is easily regenerated back into the power supplies without the losses of the Zener diode. Again, the L/10R operation may be implemented by reducing the motor winding voltage (which normally raises the current rating) and or raising the power supply voltage by a factor of 10 (or a combination of the two) and adding a resistor in series with the winding, which has a resistance of 9 times the motor winding resistance.

With the addition of a current sensor (Fig. 9) and current control logic, this drive configuration may also be used for the popular bipolar chopper drive configuration. The current sensor is most commonly a resistor between the source of the lower side transistors (Q2, Q4 for phase A) and ground. The current sense resistor, or a hall current sensor, may also

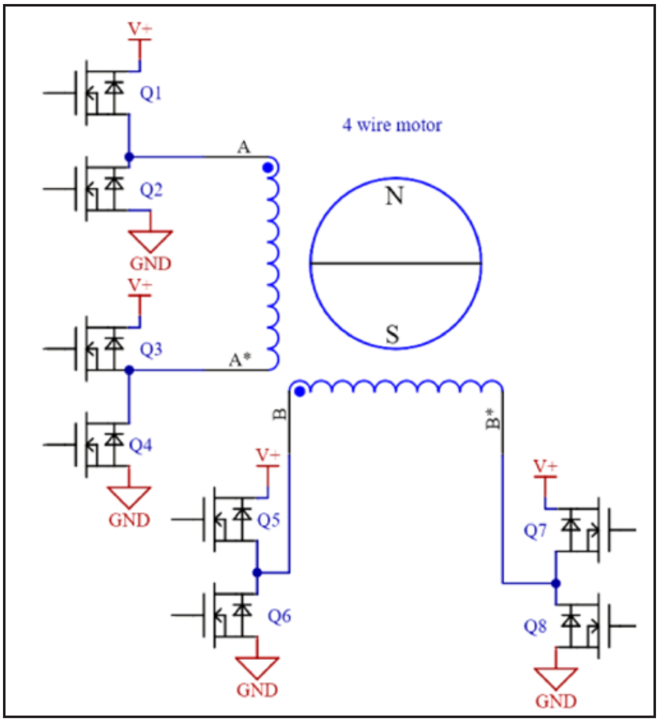

Figure 8 Bipolar driver.

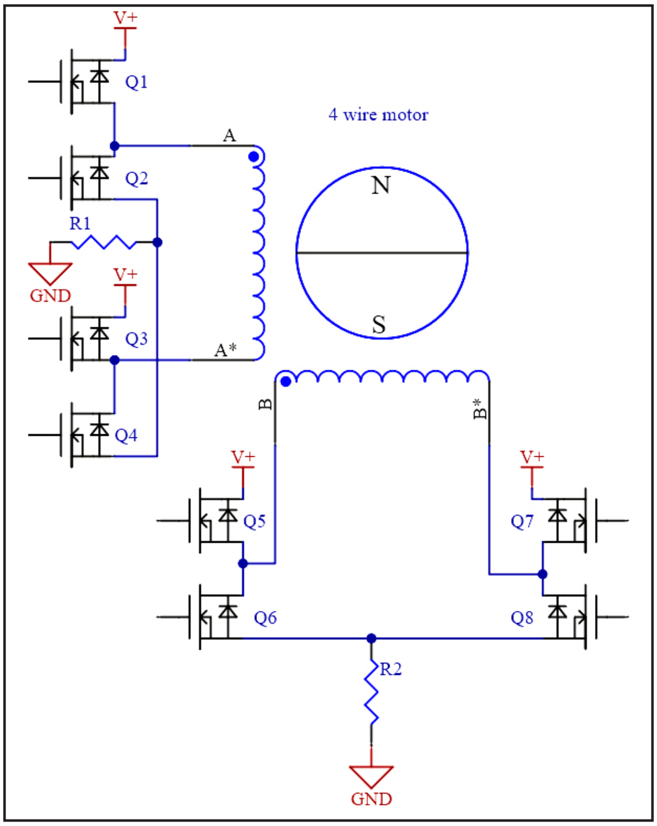

Figure 9 Bipolar drive with current sense.

directly measure the current through the windings. While either only Q2 or Q4 is on at one time (while both on bypasses the current sense resistor), the current can be measured with direction of current flow corrected by knowing which side of the lower bridge transistors is turned on at the measurement time.

The bridge may be driven as a positive drive voltage (Q1, Q4 on), a negative drive voltage (Q2, Q3 on), or recirculate (either Q2, Q3 on or Q2, Q4 on). The bridge may also be operated in a rapid decay mode by only having either Q2 or Q4 turned on, with the catch diode (or body diode) of Q3 or Q1 providing a path for current to flow back to the power rail. Recirculate mode keeps the winding shorted by two transistors, keeping the voltage across the winding low, which keeps the current from decaying quickly. The rapid delay mode causes the full power supply voltage to be across the winding in a direction that opposes the current flow until the current flow has decayed to zero (at which point the catch or body diode stops conducting). This is useful both to capture regenerated power from the motor and to rapidly drop the current when preparing to reverse the phase of the current through the winding.

Basic Hysteretic Current Control

When the motor is operating from a voltage greater than the continuous motor voltage rating (motor resistance * continuous motor current), that is not just an L/R configuration; the bridge must switch or chop to keep the current controlled within the motor ratings. This is commonly accomplished using a small sense resistor at the bottom of the bridge (US5952856). The current control is typically peak sensing with a fixed frequency. The input to the driver may be just the phase, or a phase and a current level. The current level may have either a few levels (half-step, quarter-step) or many levels (commonly 256) for microstepping. With hysteretic control, either Q1and Q3 are switched on (for a positive current), or Q3 and Q2 are switched on (for a negative current) and the voltage across R1 rises to the desired threshold for the commanded current. The phase then goes into regenerate mode where Q2 and Q4 are turned on (alternately Q1 and Q3 for some drivers). The winding is effectively shorted with the only voltage drop being the losses in the winding resistance and the transistors; this causes the current to slowly ramp down. When the next chopper period is started by the clock, the two alternate transistors are again switched on, allowing the driver to sense the current and the resistor voltage is again monitored.

Fast Decay Mode

A later addition allows the regeneration cycle to be replaced by a rapid decay cycle, as determined by either the driver or the attached processor. After the upper current threshold has been reached, the opposite low-phase is energized (Q4 turned on and Q2 turned off if it was a positive current cycle) and both upper transistors (Q1 and Q3) are turned off. The winding sees the full power supply voltage in a direction that causes the current to rapidly fall, which continues until the next cycle of the chopper clock. Some drivers implement a lower threshold on the current, which allows the device to go into recirculating mode once the threshold has been reached by turning on both lower transistors (Q2, Q4) to slow the current decay rate.

Minimum Current Problem

The current sensing PWM modulation has a problem near-zero current. The current comparator normally has a lockout period on the comparator so that it does not trigger the turn on noise of the transistor (gate current spike and reverse recovery period of the body diodes). The drivers also commonly have a minimum on time to allow the transistors to completely turn on. The sum of these two time periods adds up to set a minimum on time. A 1 uS minimum on time with a 40 uS chopping period (25 kHz chopping frequency) is a 2.5% minimum on time. If the motor is being operated from a drive voltage that is substantially above its continuous operating voltage (for example a 3.3v motor with a 48v power supply), the minimum on time can be a substantial fraction of the full-rated current (48v/3.3v *1us/40us = 36%!) . For full-step operation, or even half-step, this is not an issue; but for high-resolution microstepping, the minimum on time can introduce a significant distortion around the zero current point, making for a jump in rotor position as the current of each phase passes through zero commanded.

Subharmonic Oscillation

The hysteretic current controller tends to have a mode where the motor chopping is audible, even though it is being chopped at 25kHz. When just holding a current, if the current starts out a bit lower than average, then the turn on time is longer to get the winding up to current; the recirculation time is thus reduced. The following cycle the current has not decayed down as far as the previous cycle, causing a shorter turn on time to reach the current threshold. This leaves a longer recirculation time, causing the current to decay to a lower level. The cycle now repeats. This causes a current variation at one-half the chopping frequency. The 12.5 kHz can make a high-frequency squeal. The circuit may also find a similar instability at one-third the chopping frequency, now moving the acoustical noise to 8.33 kHz — well within the hearing range. It is quite common to hear the stepper motor drivers “singing.” This is *not* a desirable sound!

Mid-Frequency “Resonance”

The mid-frequency resonance operates almost like the subharmonic oscillation, but comes from a different mode of operation. With a current-controlled driver, as the motor reaches a critical speed, the back-EMF of the motor combined with the commanded step rate causes the current drive to not quite reach the desired current. This slight reduction in current reduces the motor torque, causing the motor to slightly slow, which then reduces the back-EMF. The chopper drive is then able to bring the current up to the commanded level, causing the motor to speed up again; this cycle then repeats. The motor operating at this speed sees an unstable speed of operation, causing rough motion. It is usually called a “resonance” in the literature, but it is really a limit oscillation, as the driver switches back and forth from current control to just a voltage drive. The resulting unstable shift in the phase of the current applied to the motor varies between these two modes of operation, and gives rise to the instability at this critical speed.

Second- and Fourth-Quadrant Operation

When the motor is operating in braking mode, i.e. — positive torque with negative speed or negative torque with positive speed — the motor is acting as a generator. The back-EMF causes the current to rise when the windings are shorted. The basic hysteretic control has difficulty accurately regulating the current, and the ability to precisely control the motor suffers. There are a couple of techniques to tame regeneration, as well as the zero-current control problem.

Anti-Phase

Anti-Phase (Fig. 10) constantly switches modes between the opposite pairs of transistors; either Q1and Q4 are on, or Q2 and Q3 are on. A zero-average voltage is obtained by operating the bridge at 50%, or half the time full-voltage positive, half the time full-negative. The advantage of this is that the applied voltage is smoothly variable, from full-positive through full-negative voltage, allowing the current to be well controlled through zero. As exactly one low-side transistor is always on, the current may be continuously monitored and the duty cycle can be adjusted to control the current, whether the winding is accepting power or generating power. The anti-phase current controller typically has tuning with damping capabilities that help eliminate the subharmonic oscillations.

Not surprisingly, the anti-phase phase drive is more complex to sense and control the driver. It unfortunately also maximizes the ripple current in the motor, which generates unwanted heat. It also applies a higher RMS voltage to the winding than the other methods. The core losses are a function of RMS voltage and frequency, so again this contributes to higher motor temperatures — even if the motor torque is low. The measured temperature rise in a motor with zero-average current was measured to be on the order of 20C from this combination of effects.

Gated Anti-Phase

The advantages of anti-phase for controlling current and for good control through zero-current can be combined by using a method known as gated anti-phase (Fig. 11). This method is used by QuickSilver Controls and is described in Patent US59778737. The voltage to be applied to the motor for the following cycle is determined from a model of the motor. The duty-cycle necessary to cause the anti-phase signal to generate this voltage is determined. A gate is then applied to the drive signal, adding at least the minimum turn on time before the directional reversal signal at the start of the cycle, and enough after the transition to result in the desired voltage to the driver. Note that as the motor is being accurately modeled (using position feedback), the need to physically measure the motor current is eliminated, simplifying the hardware.

Gated anti-phase provides good current control through zero-current, it provides good 4 quadrant control, and it minimizes the applied RMS voltage to the motor, significantly reducing motor heating. The sub-harmonic oscillations are also eliminated, making for a noticeably quiet drive. As this drive is always actually operating in voltage mode, there is no mid-frequency resonance.

The next installment of this series of articles will cover feedback methods and various closed loop control options. **PTE**

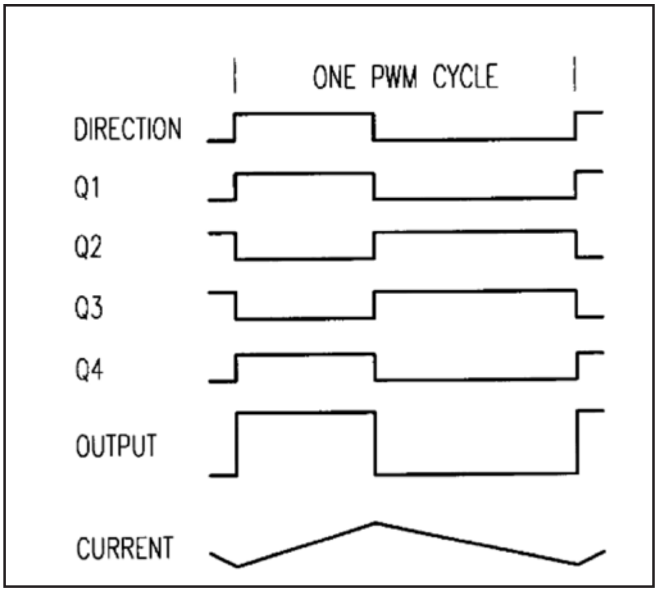

Figure 10 Anti-Phase

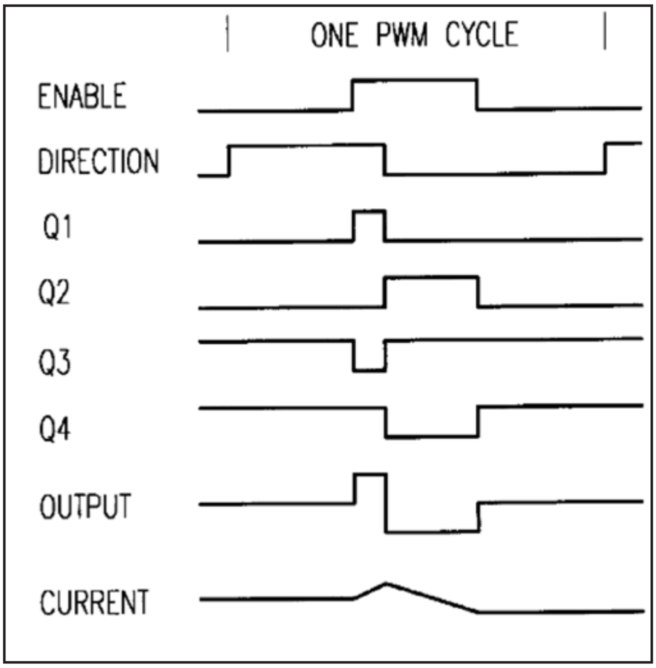

Figure 11 Gated anti-phase.

Donald P. Labriola II, president and founder of QuickSilver Controls, Inc., specializes in servo controllers and motors, with a special focus on cost-effective motion control. He has been granted eleven US patents as well as numerous international patents. His background includes over 40 years of motion control including 20 years in medical instrument design. He enjoys gardening, camping and Ham radio — and motion control!