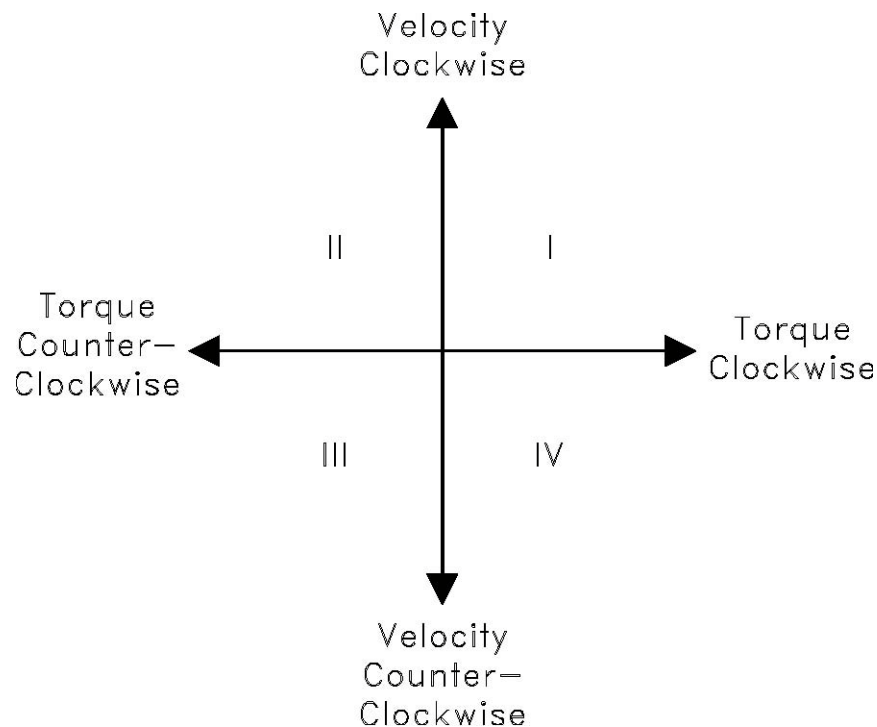


Torque Control vs. Speed Control

By Dan Williams, MS Kennedy Corp.; Revised 9/19/2013

Introduction

In a speed controller, the motor's speed (or velocity) is being controlled. There is an element that detects speed, whether it be a tachometer or some sort of encoder. This monitoring element provides the feedback to the speed controller to either increase or decrease speed. The speed controller controls the speed of the motor by increasing or decreasing the applied voltage to the motor. In a PWM controller, by controlling PWM duty cycle, the proportional voltage is controlled. As voltage is applied, there is a resulting current flowing through the motor winding. This current provides torque to spin the motor. This current is not being controlled directly, but through applied voltage. A speed controller can control speed in either a clockwise direction or a counterclockwise direction by applying a positive or negative voltage. This is referred to as a two quadrant controller; clockwise torque in a clockwise direction and counterclockwise torque in a counterclockwise direction



Four Quadrant Control Chart

In systems where speed remains fairly constant or doesn't need a quick change due to a high bandwidth control signal, a speed controller is adequate. To implement a two quadrant speed control amplifier, an understanding of the PWM cycle is necessary.

Speed Control

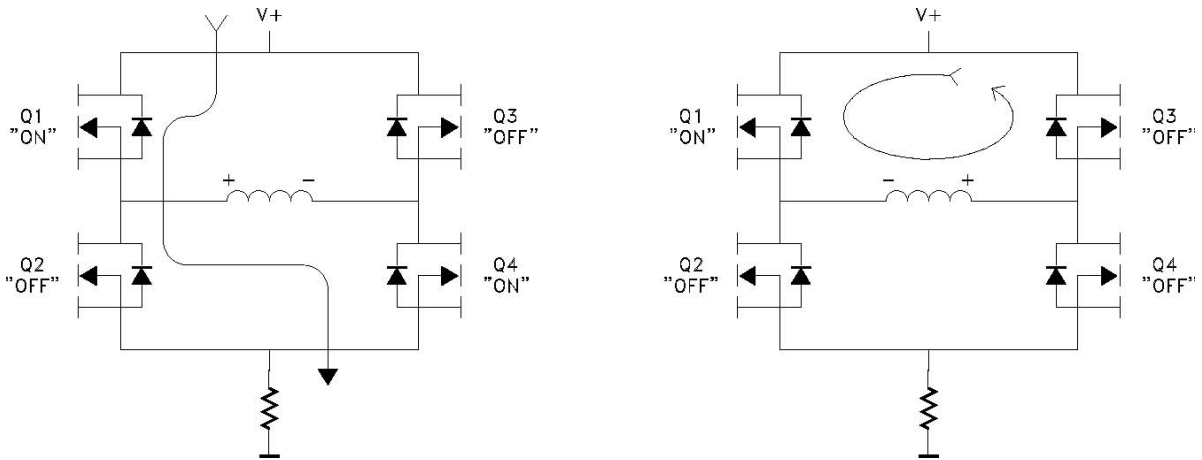


Figure 1
2 Quadrant Speed Control, 1 PWM Cycle

Figure 1 is an example of typical 2 quadrant speed control. The upper MOSFET switch (Q1 or Q3) acts as the direction steering element, and the lower MOSFET switch (Q2 or Q4) gets PWM modulated to control the voltage in the motor winding. When Q1 and Q4 are on, the current flows through Q1, through the motor winding, through Q4 and to the return through the sense resistor at the bottom of the bridge. When switch Q4 turns off, because current in an inductor cannot change instantaneously, the voltage on the motor winding will reverse. This is due to the decaying magnetic field. The resulting current will “free-wheel” through Q3’s body diode and back around the top loop. Notice that there is no current flowing in the sense resistor. During the “OFF” portion of the PWM cycle no current gets sensed. The current that is flowing is not controlled because it is left to decay through the loop. Depending on the duty cycle of the PWM, the current may decay back to zero and stay there until the next cycle. Because the current is only being viewed during a portion of the PWM cycle, this method does not lend itself to 4 quadrant torque control.

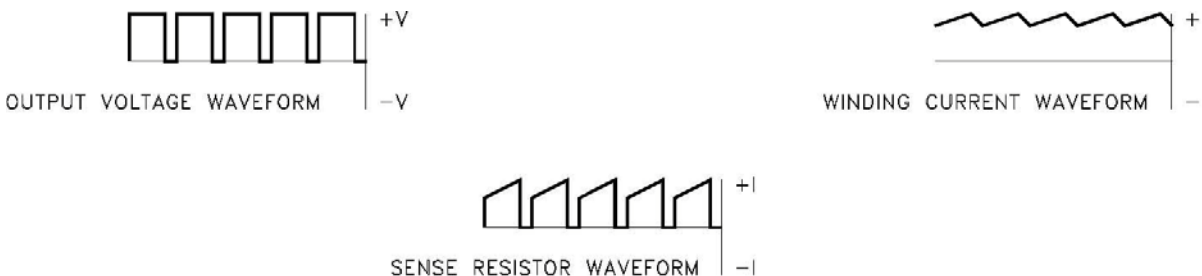


FIGURE 2: SPEED CONTROL WAVEFORMS—NEARING FULL SPEED (FORWARD)

Figure 2

As seen in Figure 2, the sense resistor sees the portion of the current that’s flowing during the “on” time of the transistor Q1. During the “off” time, the current does not get sensed and cannot be used for closed loop current control.

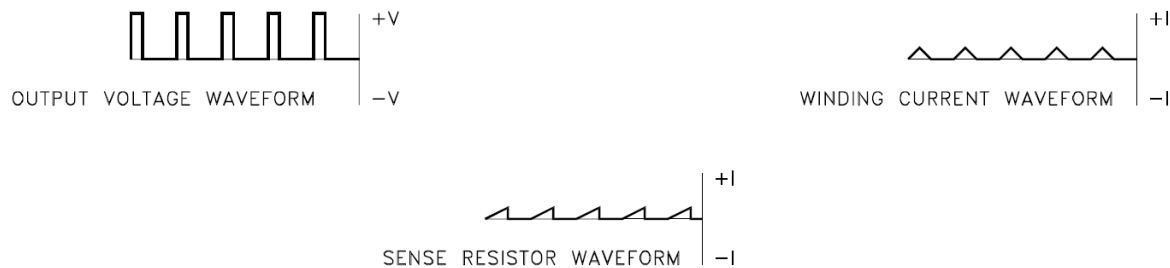


FIGURE 3: SPEED CONTROL WAVEFORMS—LOW SPEED (FORWARD)

Figure 3

As seen in Figure 3, as the demand for speed gets reduced, there is a smaller and smaller pulse width resulting in a lower voltage on the motor winding. The current through the winding is becoming discontinuous, that is, the current through the winding is decaying to zero during a portion of the PWM “off” time. This further demonstrates the limited usefulness of this switching scheme for any type of tight current control.

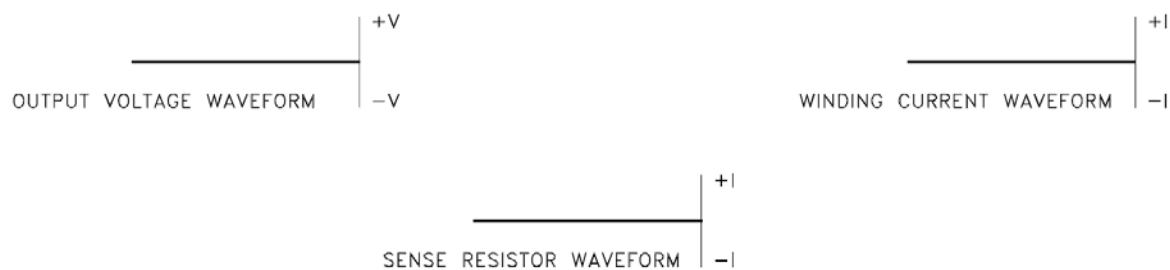


FIGURE 4: SPEED CONTROL WAVEFORMS—ZERO SPEED

Figure 4

As seen in Figure 4, when the requirement for zero speed is reached, all PWM’ing is stopped. There is no voltage on the motor winding and there is no current flow. This is not acceptable for any closed current loop application.

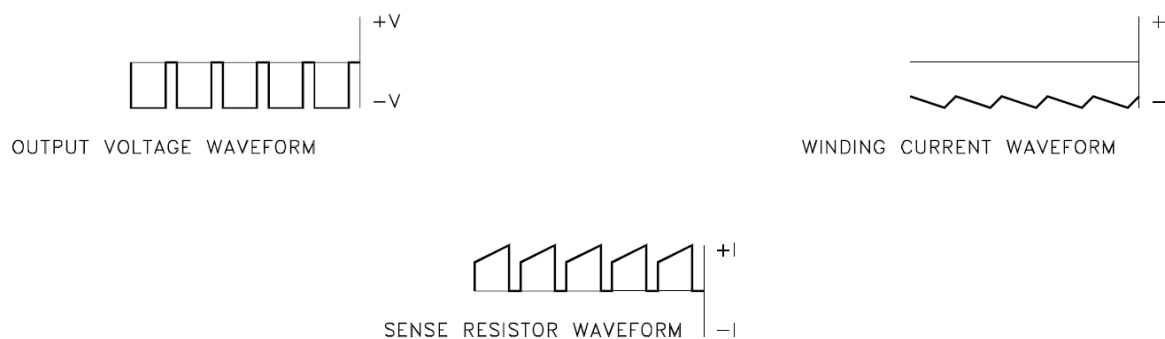


FIGURE 5: SPEED CONTROL WAVEFORMS—NEARING FULL SPEED (REVERSE)

Figure 5

Figure 5 shows direction reversal. The voltage is reversed on the motor winding because opposite transistors are conducting. The resulting current through the motor winding is reversed. However, the sensed current through the sense resistor is uni-polar. It does not show any direction reversal of current. This is also not acceptable for any closed current loop application.

“Pseudo” Four Quadrant Control

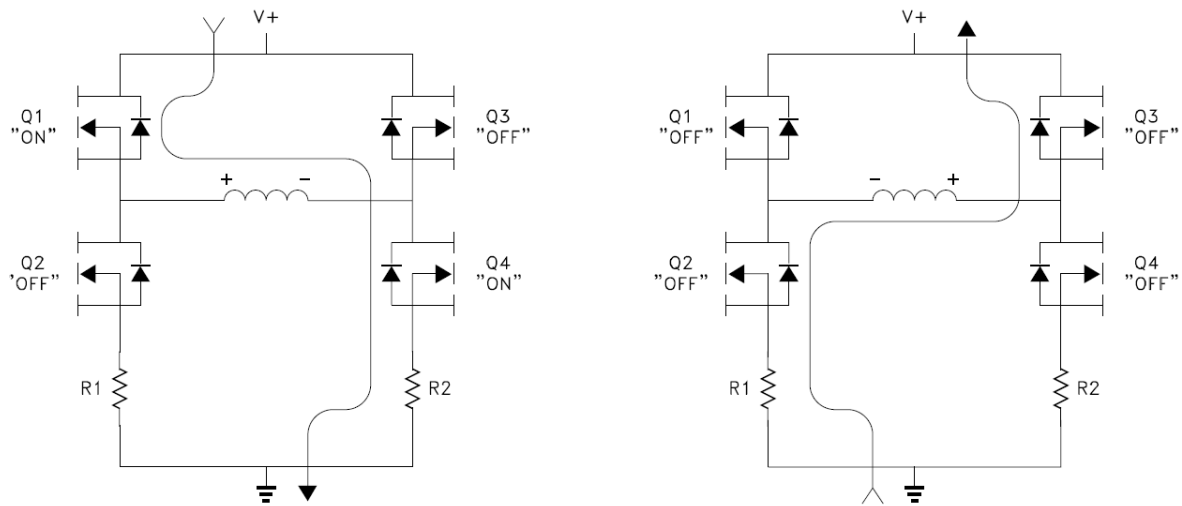


FIGURE 6: PSEUDO FOUR QUADRANT CURRENT (TORQUE) CONTROL, 1 PWM CYCLE

Figure 6

Figure 6 is an example of what some call 4 quadrant control. Both the upper MOSFET switch (Q1 or Q3) gets PWM modulated along with the opposite lower MOSFET switch (Q2 or Q4, respectively). Shown is the current path when the MOSFETs Q1 and Q4 are on. The sensed current goes through the sense resistor. During the second portion of the PWM cycle, the 2 transistor switches get turned off and the current decays through the body diodes of Q3 and Q2. The decaying current also goes through the sense resistor, allowing proper viewing of the current at all times. This would appear to be adequate for 4 quadrant torque control. However, consider what happens at very low duty cycles approaching zero (zero current). The PWM modulating of MOSFET switches Q1 and Q4 gets shorter and shorter in duration. Eventually the PWM gets so small that the switches don't get turned on at all. This means that there is no current flowing in the sense resistors and that there is nothing to use for controlling the current loop. The loop becomes discontinuous at this point. There is no torque control around zero.



FIGURE 7: PSEUDO 4 QUADRANT CONTROL WAVEFORMS—NEARING FULL TORQUE (FORWARD)

Figure 7

As seen in Figure 7, there are 2 transistors switching on and off. However, look at the voltage that's being switched to the motor winding. It is exactly the same voltage levels as the two quadrant bridge. Therefore, the current can only be conducted in at the rate of the voltage supply on the bridge. To increase that, the supply voltage has to be increased. One more interesting thing to note about this topology, there are now two sense resistors viewing the current through the bridge. One resistor sees the current during the “on” portion of the PWM cycle, and the other resistor views the current during the “off” portion of the cycle. By manipulation of the resulting two current waveforms from the resistors, a acceptable feedback waveform will be obtained. How this processing of the two current waveforms is accomplished is beyond this application note. It will have amplitude and direction information for the current through the motor winding.



FIGURE 8: PSEUDO 4 QUADRANT CONTROL WAVEFORMS—LOW TORQUE (FORWARD)

Figure 8

Figure 8 shows a lower torque switching waveform as the PWM duty cycle gets smaller and the resulting current gets lower. It is beginning to be evident just what will happen as the commanded current approaches zero. The PWM waveform gets smaller and smaller until there is no switching.



FIGURE 9: PSEUDO 4 QUADRANT CONTROL WAVEFORMS—ZERO TORQUE

Figure 9

Figure 9 shows zero commanded current. There is no switching and there is no current flow. However, there is no feedback current waveform available to use as a feedback for a current loop. The loop has basically gone discontinuous and out of control. This is not an acceptable situation for good control of a servo loop where the loop spends a lot of time around zero.



FIGURE 10: PSEUDO 4 QUADRANT CONTROL WAVEFORMS— NEARING FULL TORQUE (REVERSE)

Figure 10

Figure 10 shows reversal of the PWM waveform for producing a negative torque. The resulting currents through the two resistors reverse as well, giving the necessary voltages for reconstruction of the current through the winding. As increasing current is demanded from the bridge, increasing PWM duty cycles are seen on the gates of the bridge. The only difference is that opposite sets of transistors are PWM modulated. This brings up another characteristic of this method of producing a current loop. As positive current increases in the motor winding, a larger PWM duty cycle is seen at the gates. As negative current increases in the motor winding, larger PWM duty cycles are also seen at the gates, but opposite transistors. The creation of the PWM waveform is unipolar. There is no direction information inherent in the waveform. There is a direction determining (polarity sensing) circuit that decides which pairs of transistors to switch. At some point very close to zero current, the polarity must reverse and opposite transistors switch. It cannot happen exactly at zero. This adds to the error resulting around zero current that causes a huge problem in servo control. An offset in this polarity sensing circuit will cause an instability in the current loop because the loop is no longer linear around this point.

Full Four Quadrant Control

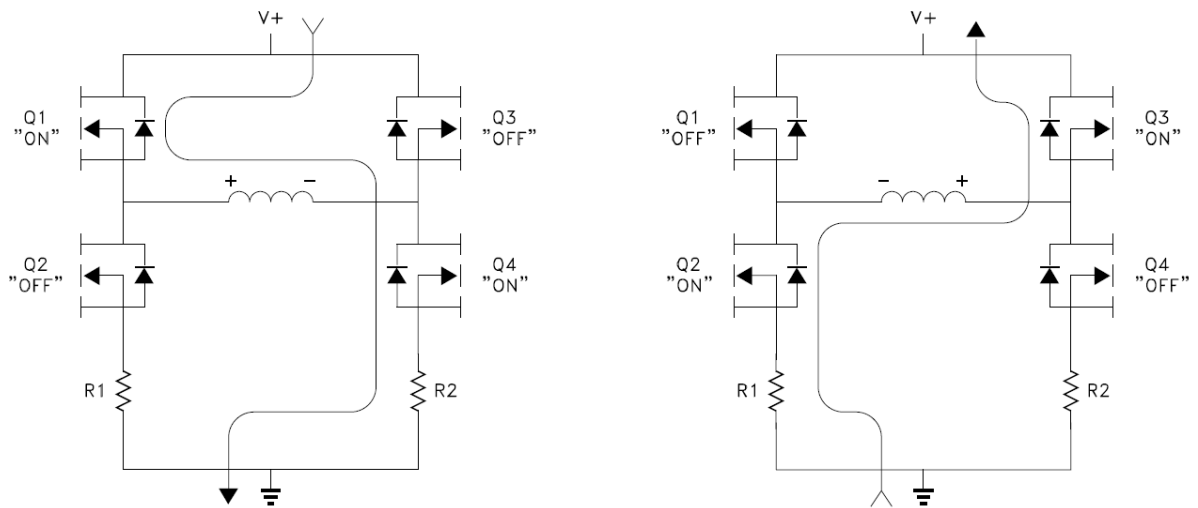


FIGURE 11: FULL FOUR QUADRANT CURRENT (TORQUE) CONTROL, 1 PWM CYCLE

Figure 11

Figure 11 is an example of a full 4 quadrant torque control modulation scheme. MOSFETs Q1 and Q4 get turned on during the first portion of the PWM cycle. The current flows through R2 and gets sensed. At the end of the first portion of the PWM cycle, MOSFETs Q1 and Q4 get turned off and MOSFETs Q3 and Q2 get turned on. (There must be allowance for a small amount of deadtime between Q1 and Q4 off and Q3 and Q2 on. Otherwise, there will be shoot-through and the bridge will be destroyed.) This method of modulation is known as “locked anti-phase” PWM. During the first portion, current will flow through R2 and get sensed. During the second portion of the PWM cycle, current flows through R1 and gets sensed. Even during the deadtime, current will flow through one of the resistors. Current gets viewed at all times. There is one thing to note that makes this scheme special. At zero current, the modulation is exactly 50% for each transistor pair. There is zero net average current going through the winding of the motor, but there is always current flowing which allows the circuit to sense it at all times. The control loop will always be controlling the current even when going through zero.



FIGURE 12: TRUE 4 QUADRANT CONTROLLER—NEAR FULL TORQUE (FORWARD)

Figure 12

As shown in Figure 12, the voltage waveform across the motor winding has twice the available amplitude as the other examples. This means that the current can be ramped up and down at twice the rate as the others. This figures into the bandwidth equation as twice the available bandwidth. The two resistors accurately measure the raw current information from the two legs of the bridge. Manipulation of the two waveforms will result in an accurate representation of the current going through the motor winding.



FIGURE 13: TRUE 4 QUADRANT CONTROLLER—LOW TORQUE (FORWARD)

Figure 13

Figure 13 shows as the commanded current goes down, the duty cycle gets shorter. However, it does not go to zero, as shown in the previous example. As the commanded current goes towards zero, the resulting PWM waveform goes closer and closer to 50%



FIGURE 14: TRUE 4 QUADRANT CONTROLLER—ZERO TORQUE

Figure 14

Figure 14 shows the various waveforms when zero current is commanded from the bridge. The duty cycle of the PWM is exactly 50%. This means that there is always current flowing through the motor winding, but the net average of the current is exactly zero. Since there is always current flowing, there is always a feedback signal to use to close the current loop. The loop is always in control, even exactly at zero.



FIGURE 15: TRUE 4 QUADRANT CONTROLLER—NEARING FULL TORQUE (REVERSE)

Figure 15

Figure 15 shows a negative current being commanded of the bridge. The duty cycle of the PWM goes below 50%. That means that above 50% there is positive current flow, and below 50% there is negative current flow. The PWM generation is bipolar. There is no point of indecision from any polarity detection circuit. Any offset will show up as an error in the output current, but it will always be a linear function with no discontinuities. This true “full” four quadrant bridge will make an excellent topology for good servo control, especially around zero.

MS Kennedy’s 3 phase brushless motor torque controllers use this last scheme to provide closed loop control through zero and provide high bandwidth because of the active control of the current at all times. For applications requiring tight control of torque continuously regardless of the direction of the motor, MS Kennedy’s torque motor controllers provide the best solution in a demanding servo control environment.