MOTOR CONTROL
Tech Tips
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Introduction to BLDC Motor Torque Control
Part 2

Two-Quadrant Torque Controls

In this Tech Tip we continue our analysis of BLDC Motor Torque Control with a discussion of the simpler 2-Quadrant torque control loop. 2-Quadrant torque controlled BLDC drives are used in applications where controlled deceleration is not required and friction is sufficient to decelerate the load. This torque/speed operation is in quadrants 1 and 3, where torque and rotation are in the same direction. The advantage of 2-Quadrant control is higher efficiency, simplicity and lower cost as compared to the higher performance of 4-Quadrant control discussed in Tech Tip Issue 3. Most simple BLDC power amplifiers provide 2-Quadrant control since the simplest output stages (typically a 3-phase PWM Bridge), and the ICs that control them, allow direction reversal.

Two-Quadrant Chopping

In 2-Quadrant controllers, only the BOTTOM Arm (in a 3-phase bridge) is chopped at the PWM frequency, typically 18KHz or greater (to avoid audible interference). The TOP Arm power devices switch at the much lower BLDC commutation frequency, which is proportional to motor pole-pair count and speed. Higher efficiency is achieved since the TOP Arm power devices do not switch at the PWM frequency, resulting in approximately half the switching losses of a 4-Quadrant controller. Cost advantages can be realized since the average gate drive power consumed by the TOP Arm is lower. This results in lower power requirements for the gate drive components. One TOP Arm switch is ON for an entire commutation interval, while one BOTTOM Arm switches at the PWM rate. During the PWM ON-time of that BOTTOM Arm switch, the supply voltage, minus the motor BEMF voltage, charges the winding inductance. During the PWM OFF-time (of that BOTTOM Arm switch) the winding current freewheels between one TOP Arm switch (which remains on) and one upper flyback diode. The winding inductance is discharged by the voltage drop due to the motor BEMF. During the OFF-time (of that BOTTOM Arm switch), the freewheeling current cannot be detected by a current sensor located in either the upper or lower supply rails of the inverter. As a result, it cannot be controlled which leads to a potential problem during reversing. During a phase reversal, the duty cycle of the BOTTOM Arm switch cycle will be driven nearly to zero. The free wheeling diode duty cycle increases nearly to 100% because the BEMF acts in series with the supply voltage when the phase is reversed. The freewheeling current (not detected and thus not bounded by the current sensor) transiently increases to approximately the BEMF voltage divided by the motor impedance. This continues until the kinetic energy stored in the moment of inertia is depleted. Because the machine's mechanical time constant is usually much larger than its electrical time constant, the diode and TOP Arm switch experience considerable thermal stress and will likely fail if such reversals are permitted to occur. However, even if large enough power devices are selected to handle this stress, it is unlikely this abrupt torque shift would be tolerated in most systems. To avoid this abrupt torque shift, a protection circuit must be added to the 2-Quadrant controller to prevent the change-in-direction signal from reaching the commutator logic, until the motor speed is at or near zero. This can be accomplished by forcing the PWM to a zero duty cycle, which allows the speed to fall. Direction can be reversed after the speed falls below some minimal threshold: the PWM duty cycle can now be re-enabled. If the direction pin on the controller is not used (single quadrant applications) it must be tied high or low, and not be allowed to float.

Closing The Current Loop

The current sense signal is only observable during the PWM ON-time, thus the 2-Quadrant torque controller is normally operated in pulse-by-pulse or peak-current control modes as illustrated in Figure 1. In this current/torque control mode the current sense amplifier signal is applied directly to one side of the PWM comparator, while the opposite side is driven by the output of the velocity control loop. A peak current mode controller does not control duty cycle, as in a conventional control loop, instead it forces the peak winding current to follow the torque command input. The clock output of the PWM oscillator initiates each PWM pulse by setting the output of a PWM latch. The trailing edge of the PWM pulse occurs when the PWM comparator clears the latch. The latch is cleared when the peak of the positive going (positive-ramp-on-a-pedestal) current sense amplifier output (and PWM comparator input) equals the torque command at the other PWM comparator input. This control technique relies on the assumption that peak current is, to a good approximation, proportional to average current. When this approximation is valid, the peak current mode controller provides all the usual feed-forward properties of current mode control, and reduces the order of the system dynamic by one.

Stability Issues

It is well known that the peak current mode controller is subject to subharmonic oscillations at duty cycles exceeding 50%. If the desired torque control range can be met with duty cycle ratios at or below 50%, oscillations can be prevented by simply clamping the torque control input command range. For duty cycles above 50%, slope compensation can be employed to extend the useful operating range of the modulator. This compensation ramp (proportional to output voltage) is added to the ramp, and is used to cancel the effect of inductor current. However, the user is warned that slope compensation for a BLDC controller is much more complicated than slope compensation typically employed in simpler constant output voltage power supply applications. In BLDC motor control, the output voltage of the controller varies with both supply voltage and motor speed and thus, the offending inductor downslope (and slope compensation) are much less predictable. To operate properly, the slope compensation ramp must be designed to account for this variation. These circuits tend to be complex. Over compensation can be used to insure stability, but this reduces current loop accuracy.

A more persistent problem occurs at light loads where the winding current becomes discontinuous. Even with proper slope compensation, the gain of the peak current mode control is drastically

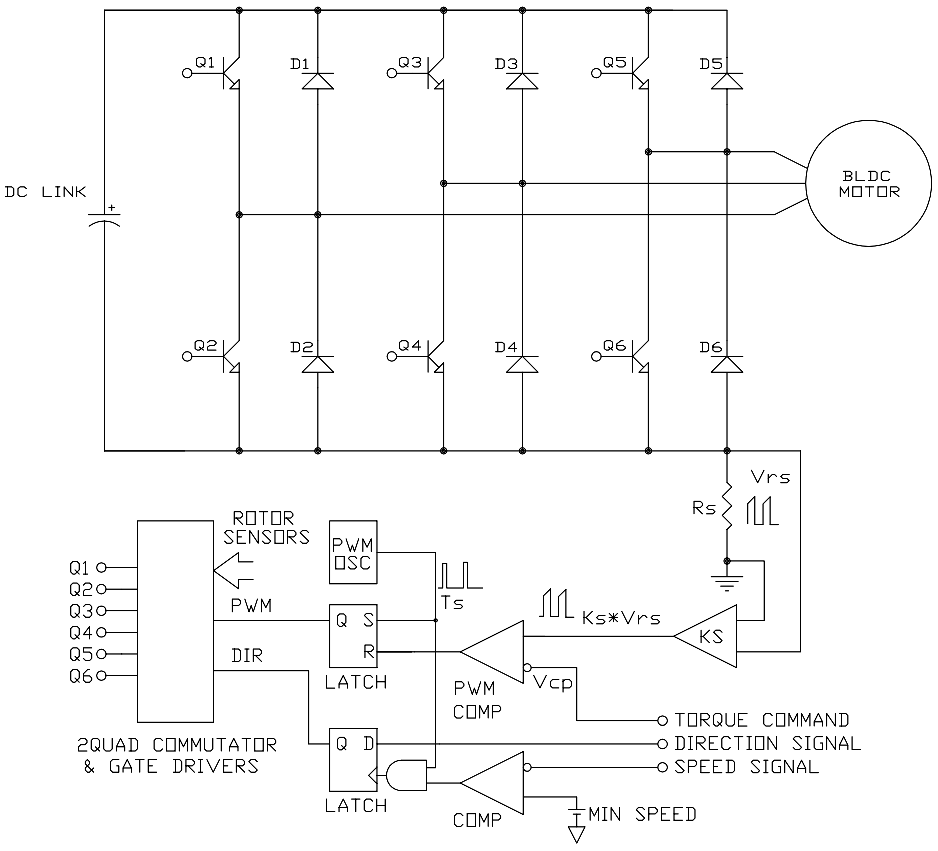

Figure 1: Two Quadrant Torque Control
(Only lower transistors are chopped)

reduced and becomes nonlinear at the continuous/discontinuous current mode boundary. This is particularly troublesome in position control applications and is one of the main reasons average current mode control is preferred in 4-Quadrant BLDC servo applications (as discussed in Tech Tip Issue 3).

In the average current mode controller the loop dynamics shift at the continuous/discontinuous current mode boundary, since the single pole response assumption no longer applies. This causes the control to operate more sluggishly. However, the current amplifier gain is relatively consistent as it is a function of the average winding current. The net result is that the control operates properly even at light loads.

Frequency Compensation

Since a peak current mode controller does not employ a current error amplifier, frequency compensation for the current loop must occur in the outer velocity loop. The compensation required remains at a reduced order (for the continuous winding current operating range) because peak current mode control still eliminates the high frequency pole due to the motor L/R time constant. Please refer to Tech Tip Issue 5 for a discussion of outer velocity loop frequency compensation.

Supplementary Over-Current Limit Circuits

Over-Current limiting and Over-Current shutdown features can be used in 2 & 4-Quadrant applications by adding a comparator to compare current sense amplifier output to a fixed trip threshold. If used, the Over-Current trip threshold is set above the normal current loop working range while the comparator output is logically OR'ed with the PWM comparator output to drive the reset input of the PWM latch. A current limit fault (outside the normal working range of the modulator) causes the duty cycle to prematurely terminate on a cycle-by-cycle basis. Additional current limiting circuitry can latch the drive completely OFF or provide a hiccup type restart mode. In either case these circuits provide a secondary mechanism to protect the drive from damage.

A Soft-Start feature (as discussed in Tech Tip Issue 1) can be created by forcing the duty cycle to ramp up slowly, i.e., limit the rate at which the current or voltage loop error amplifier output rises during motor startup.

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