Low Voltage, High Slew Rate Op-amps for Motor Drive Circuits

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TEXAS INSTRUMENTS

The requirements for operational amplifiers and other ICs used in motor control systems have increased because of the need to extract higher performance from a motor while maintaining low system cost. Measuring motor current is an easy and inexpensive way to understand the torque and direction of the motor, so current sensing forms the backbone of many common motor control schemes for the three common DC motor types: stepper, brushed DC and brushless DC (BLDC).

Motor current relates proportionally to torque, allowing a motor controller to monitor the motor load through current sensing. It can also protect the motor from over-torque or overload conditions in the event of a jam or some other system failure. Typically, motors are controlled with a pulse width modulation (PWM) scheme generated by a controller driving different MOSFET half-bridge driver configurations. An H-bridge is used for brushed DC motors as shown in Figure 1, dual H-bridge for stepper motors, or triple half-bridge for BLDC motors. When the MOSFETs are switched on and off with a PWM input, the inductance of the motor acts like a low pass filter and produces an RMS current that depends on the duty cycle of the PWM signal.

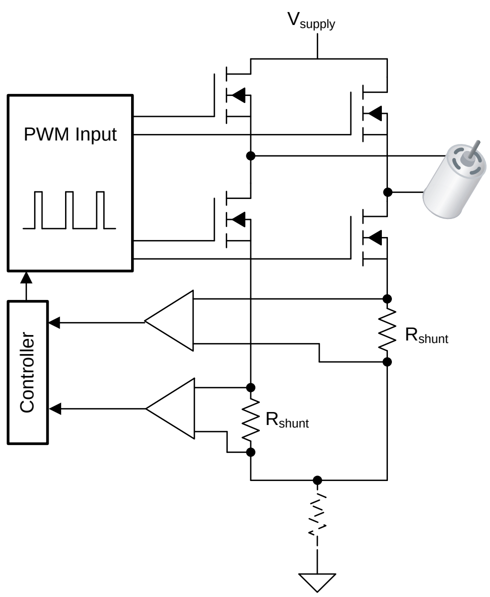

Figure 1. H-Bridge Motor Driver with Low-Side Current Sensing

The simplest and lowest cost motor control schemes use a single low-side shunt resistor (shown as a dotted resistor to ground in Figure 1) and sum the leg currents to get an average value used for torque control and simple fault detection like over-torque or overload. In many cases, the demands on the current sense amplifier are lower because over-torque conditions can be monitored over multiple switching cycles with lower accuracy requirements. These schemes generally do not push the boundaries of frequency or duty cycles either.

However, the single summing shunt method may not provide the level of information required to use control schemes such as field oriented control (FOC) in BLDC motors. Accurately measuring the current through each leg of the driving circuit is used to maximize torque, efficiency or optimize other system goals. This can be seen in Figure 1 where each leg has its own shunt resistor (labeled Rshunt). FOC control schemes have more demanding requirements for the low-side current sense amplifiers because measurement accuracy is critical to the control algorithm, PWM frequencies and duty cycles are likely to be more extreme, and measurements are made in each PWM cycle. DC measurement accuracy is important for FOC control schemes, requiring consideration of the offset voltage, rail to rail behavior and input common mode range of the op-amp.

Let’s look at how a typical low-side current sense amplifier responds to a sudden large current in the shunt resistor. When a PWM pulse is applied, the low side transistor turns on and the current steps up from nearly 0 A through Rshunt to the value of the motor winding current. This current creates a voltage jump and therefore a large signal input into the non-inverting pin of the op-amp. Any large signal step Figure 1: H-bridge motor driver with low-side current sensing. into an op-amp’s inputs causes the amplifier to go into slew limit, where the rise time is determined by how fast the amplifier can charge the Miller capacitance between the input and output stages of the amplifier. Once the signal is within a few hundred millivolts of the final value, the small signal response of the op-amp starts to take over and the signal settling time is determined by the AC response of the op amp circuit. The key is that the overall settling time is dictated by the slew rate and the small signal settling time of the op-amp, as seen in Figure 2. The amplifier must settle before the

PWM cycle ends so that the controller can make an accurate measurement. For a given low-side current sense amplifier circuit, the settling time is constant, meaning that the there is an upper limit for the PWM frequency and a lower limit for the duty cycle.

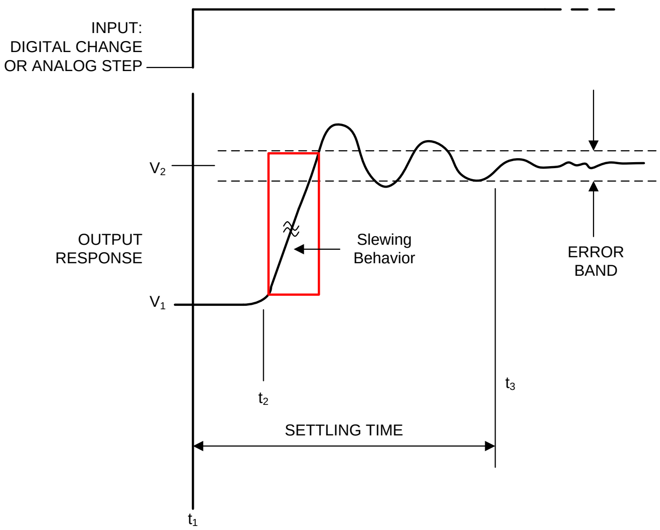

Figure 2. Large Signal Response of an Op-Amp

So what can be done to get a shorter acquisition time? One option is to choose an op-amp with a higher slew for the current sense circuit. Figure 3 shows a simple comparison of two op-amps with different slew rates driving the same load. One has a slew rate of 13 V/µs and the other has a slew rate of 2 V/µs. It is easy to see that the higher slew rate amplifier has a much shorter overall settling time because less time is spent in the op-amp's slew rate limit. The larger the input step, the more time the op-amp will spend in slew limit.

Looking at TI's op-amp catalog, it is easy to see that high slew rate devices are usually high bandwidth devices. Because motor drive systems do not usually require passing high frequency signals, using high bandwidth amplifiers comes with some substantial trade-offs, including increased stability concerns and higher cost. Arguably the biggest tradeoff is that high bandwidth devices need higher quiescent current (I_q) making them unsuitable for applications which are power constrained like battery operated tools and drones.

1.1 Trademarks

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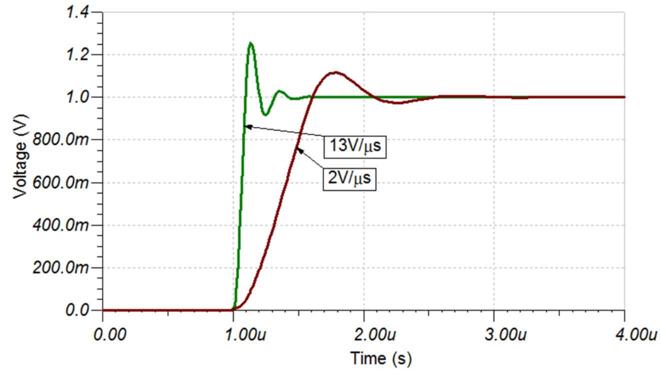

Figure 3. Slew Rate Comparison

TI now has the TLV9052, featuring a 13 V/µs slew rate, 5 MHz bandwidth and only 330 µA I_q. The TLV9052 represents a significant improvement over other low voltage (<7 V supply) op-amps with similar bandwidth, which typically have slew rates ranging from 2 V/µs to 10 V/µs and 400 µA to 2 mA of I_q. This combination of features in the TLV9052 makes operational amplifier an attractive way to extract more performance from a motor drive system while maintaining low system cost and power consumption. If a simpler motor control system is used with only a single shunt, consider using the TLV9002 which has a good trade-off of specifications and price.

1 Related Documentation

For more information on slew rate, bandwidth and stability please see TI Precision Labs Op Amps videos:

- Slew Rate
- Bandwidth
- Stability

More information on designing a low-side current sense amplifier with an op amp can be found in the following TI Circuit Cookbooks:

- Single Supply Low-Side Current Sensing SBOA215
- Bidirectional Low-Side Current Sensing SBOA223

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