Monitor PWM load current with a high-side current-sense amplifier

Maurizio Gavardoni and Akshay Bhat, Maxim Integrated Products - March 03, 2011

Accurate high-side current sensing is essential for automotive-control systems, such as those for EPS (electric power steering), automatic gear shifting, transmission control, engine fuel-injection control, braking-valve control, and active suspensions. All of these applications require precise regulation of the current through a motor or solenoid. The current sets the torque of the motor or the drive of the solenoid. You can design a precision, high-side current-sense amplifier to monitor inductive load currents over a wide range of input common-mode voltages. The circuit is suitable for applications in which the input common-mode voltage becomes negative due to inductive kickback, reverse-battery conditions, or transient events.

Sense current in EPS

Unlike conventional power-steering systems, an EPS system has no hydraulic pump or fluid. Instead, it features an electric motor that attaches to the steering rack through a gear mechanism. When the driver turns the wheel, a steering sensor detects the wheel’s position and rate of rotation. The system then feeds this information, along with input from a steering torque sensor in the steering shaft, to the power-steering-control module. To determine the required steering assistance, the control module also takes inputs from the vehicle’s speed-sensor, traction-control, and stability-control systems (Figure 1).

An interface with the power module then allows the control module to regulate the amount of current in the motor. Increasing the motor current increases the power assistance, and vice versa. You control motor current by feeding a PWM (pulse-width-modulated) voltage across the motor with an H bridge (Figure 2). An associated truth table summarizes the various modes of operation for a full H-bridge circuit (Table 1). The motor presents an inductive load. You determine torque by averaging the resulting ripple current. This current represents the resulting power assistance the circuit provides to the driver.
You use a current-measuring device to monitor motor current and provide real-time feedback to the control module. The module adjusts the PWM duty cycle until the current reaches its target value. You can insert a low-value sense resistor in series with the current path to produce a small reduction in voltage. A current-sense amplifier on that differential voltage indicates the current magnitude.

Current-sensing approaches include low side, high side, and on the motor. For low-side current sensing, you place the sense resistor between the H bridge and ground on the bottom of the dc bus. For high-side current sensing, you put the sense resistor between the positive battery terminal and the H bridge on the high side of the dc bus. You can perform output PWM current sensing on the motor itself.

These alternatives require trade-offs. The low-side approach is convenient but adds undesirable resistance in the ground path. It also lacks the diagnostic ability to detect a short-to-ground fault. Neither the high-side nor the low-side approach lets you continuously monitor current in the recirculation diode. PWM current sensing does allow sensing of the diode current and adds no resistance to the ground path.

A PWM current-measuring circuit entails performance constraints that are far from trivial. The circuit must contend with common-mode voltages that swing all the way from ground to the battery voltage. Thus, to reject common-mode excursions, the circuit must have not only a high range of input voltage corresponding to this swing but also an excellent CMRR (common-mode-rejection ratio) at the switching frequency and at relevant edge-rate-induced frequencies.

Common-mode transients and a minimum duty cycle for the PWM signal also impose a stringent requirement for settling time in the current-sense amplifier. For an accurate and linear response, the current-measurement circuitry must have high gain, high accuracy, and low offset voltage. Because human steering is part of the control loop, linearity and accuracy are especially critical. Any nonlinearity in the circuitry can impair the driving experience by causing oscillation or vibration when you oversteer the vehicle.
You connect the motor in a full H-bridge configuration (Figure 3). This approach lets you reverse the motor-applied voltage polarity, which enables it to rotate in either direction. The IC withstands −20 to +75V common-mode voltages, making it immune to inductive flyback, load-dump transients, and reverse-battery faults. The device also integrates an instrumentation amplifier. Its indirect current-feedback architecture provides precision current sensing with a maximum input offset voltage of 400 μV and a gain error of 0.6%. The external reference voltage supports the bidirectional current sensing that a full H bridge requires and senses unidirectional current when operating with a half H-bridge circuit. In a bidirectional system, the output voltage equals the reference voltage when the sensed current is 0A. Both adjustable- and fixed-gain flavors enable this part to provide maximum flexibility over a range of applications.

**Solenoid-drive sensing**

Solenoids find wide use as electromechanical switches in vehicles. A starter solenoid, for example, delivers a large electric current to the starter motor, which in turn sets the engine in motion. However, several automotive-control systems employ a solenoid drive for precision control. For example, a diesel-engine system for railroads relies on solenoids as sophisticated electronic-control valves. They inject the appropriate quantities of fuel directly into the engine cylinders at high pressure. You accurately control the timing of these valves with the engine-control unit to ensure synchronization with the diesel engine. The result is a relatively “green” engine that makes less noise, produces fewer emissions, and is more fuel-efficient. Other applications for solenoid control include automatic gear shifting, transmission control, braking control, and active suspensions.

The high-side switch is typically a FET whose gate you control with a PWM signal (Figure 4). When the FET is on, it connects the solenoid to the 14V battery voltage, producing a current that charges the solenoid coil. When the FET turns off, solenoid current discharges through the clamp diode and shunt resistor. By regulating the PWM frequency and duty cycle, you determine the resulting average ripple current in the solenoid. This current in turn controls the force the system applies to the actuator.

The challenges of sensing solenoid current for regulating PWM frequency and duty cycle are similar to those in the H-bridge application. Common-mode voltages at the input of the current-sense amplifier range from the battery voltage to the slightly negative level of the clamp diode’s drop.
voltage. Typical solenoids require a few amperes of current, so a clamp diode that withstands such current may develop a forward voltage higher than 1V.

Again, the current-sense amplifier’s wide input common-mode range and fast settling in response to common-mode variations suit this application. The main difference between this application and that of the H bridge is that the solenoid current always flows in the same direction; the current-sense amplifier, therefore, needs only to be unidirectional. The IC becomes a unidirectional current-sense amplifier when you connect its reference input to ground.

Lab results

You can prototype a typical application circuit for solenoids in the lab (Figure 5). You emulate the solenoid with a 2-mH inductor having a low ESR (equivalent series resistance) of 1.6Ω. The sense resistor is 100 mΩ, and a value for $R_4$, not present in the actual solenoid circuit, of 15Ω limits the maximum solenoid current, as the following equation shows:

$$I_{\text{MAX}} = \frac{V_{\text{BAT}}}{(R_{\text{SENSE}} + \text{ESR} + R_4)} \frac{12V}{(0.1 + 1.6 + 15)} \Omega = 0.72A.$$
This maximum current value is the theoretical limit the circuit reaches when the inductor is fully charged. The resistor and inductor values set the circuit’s time constant to approximately 0.12 msec, which is equivalent to 8.3 kHz. You set a gain of 80 with the external resistors $R_1$ and $R_2$ having values of 1 and 79 kΩ, respectively.

Waveforms at a PWM frequency of 5 kHz illustrate the operation of the circuit in Figure 5, with duty cycles of 80% (figures 6 and 7, respectively). The top waveform is the voltage across $R_4$, the middle is the output of the current-sense amplifier, and the bottom waveform shows the PWM signal at the drain of the PFET. Higher duty cycles yield higher current.

Thus, a precision, high-voltage, high-side current-sense amplifier allows accurate measurement with smaller sense resistors. It handles the bidirectional motor currents that you derive from H bridges, such as those in EPS systems, as well as the unidirectional solenoid currents in automatic gear shifting, transmission control, braking control, and active suspensions.

**Editor’s note:** Figure 5 was changed on March 22, 2011, to correct the placement of the gate of the P-channel MOSFET. Figures 2 and 3 were changed on July 5, 2011, to correctly display the N-channel MOSFETs.