Current Measurement in Solenoids for Automotive Control Systems

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Solenoids in Automotive Control Applications

A solenoid is a linear motor with a fixed range of travel. Solenoids may be designed for simple on-off applications, acting much like relays. For example, they are used this way in *starters* and *door locks.*

On the other hand, a *linear*, or *proportional*, solenoid is one whose position can be controlled in a precise manner. They are used to operate pistons and valves for accurate control of fluid pressure or flow in applications such as *transmissions* and *fuel injection.*

Transmissions require accurate and smooth control of pressure on clutches to change gears, and for controlling the locking torque converter. Electronically controlled transmissions may contain more than eight linear solenoids, all of which require smooth, accurate control. Common-rail diesel fuel-injection applications, with pressures in excess of 2000 psi, may require one linear solenoid per cylinder—and one at the fuel pump—to adjust pressure accurately to maintain predictable injector fuel flow.

Example: Electronic Transmission Control

The automatic transmission is one system in which electronic control is largely supplanting mechanical control because of improvements in drive quality and fuel efficiency. Previous improvements in fuel efficiency and acceleration came with the introduction of the locking torque converter. More recently, a combination of software and hardware using electronically controlled solenoids allowed easier adjustment of the shift algorithms, and provided additional benefits in transmission-shift smoothness and quality.

Overall, electronic control of the transmission allows for a simpler, more reliable, and less costly electromechanical system. Electronic transmission control systems improve the control of transmission shift points, with less abrupt gear shifting and improved shift smoothness. In addition, the flexibility of the electronic control allows for better adaptability to changing conditions. Electronic control of shift points with finer resolution allows better acceleration, improved economy, better load control, and reduced emissions, with minimal effort by the driver. In addition, the electronic control allows the transmission to shift more smoothly with varying load and acceleration.

With an electronic control system it is possible to affect the shift-control algorithm by a variety of inputs in addition to shaft speed, vacuum, and driver input. Some of these parameters include spark advance, injector parameters, input speed sensors, shift selection by wire, engine speed, throttle position, torque-converter speed/lock, ATF temperature, engine temperature, wheel-slip sensors, and inertial sensors. Combining these kinds of inputs allows a wide variety of shift optimization points, adapted to the overall operating conditions. To use these inputs most effectively, it is necessary to have a system benefiting by precise and infinitely adjustable electronic control of the shift points and shift speed.

Hydraulic control is still used to change gears in the electronically controlled automatic transmission. In contrast to the mechanical system (see Appendix), electronic control of the hydraulics in the electromechanical system is executed by linear solenoids that vary the hydraulic pressure applied to the actuators attached to the clutch packs. In order for this to work, it is extremely important to have accurate and repeatable control of the solenoid opening—which in turn allows for accurate, repeatable control of the shift points through the application of precise amounts of hydraulic fluid.

Determining Solenoid Position

The *linear solenoid's* position is controlled in a feedback loop. For example, a valve's downstream pressure can be monitored and used as a feedback signal to compare with the setpoint, adjusting the pulse-width modulation (PWM) duty cycle to control the solenoid. However, it may be difficult, impractical, or very costly to measure the downstream pressure.

A practical alternative is to establish the position of the solenoid by measuring the current through the solenoid. This is possible because the force imposed by the mechanical load on a solenoid is directly proportional to the magnetic field, which, in turn, is directly proportional to the current through the coil. Proportional control of the solenoid is achieved by a balance of the forces between the spring-type load and the solenoid's magnetic field, which can be determined by measuring the current through the solenoid.

PWM Solenoid Control

The solenoid is powered by using a microcontroller-generated pulse-width modulated input signal to rapidly open and close a FET switch in series with the solenoid and a voltage source (the car's battery). The average voltage is determined by the ratio of the waveform's *on* time to the pulse period. Changes in the pulse width and the solenoid's mechanical load cause the average current flowing through the solenoid to change. The average current is indicative of the amount of solenoid movement, and thus, fluid pressure and flow.

The relationship between solenoid movement and average current for a particular PWM waveform is established through *characterization*. While it is true that the magnetic force directly relates to the current through the solenoid, the actual mechanical force and movement are not so closely correlated, since they depend on the construction of the solenoid and the nature of the load. So, characterization is required to correlate the average current to the solenoid opening.

For example, the PWM ratio must be increased when the solenoid is first energized to overcome static friction. Once static friction is overcome, a different PWM relationship is used to move it in and out.

Measuring the Current Through the Coil

The current is thus an important indication of the solenoid's state. The most effective method of measuring the solenoid current is to measure the voltage across a resistive shunt connected in series with the solenoid, the battery, and the switch. There are several different ways to configure this series circuit for switching and voltage measurement.

Low-Side Current Sense with High-Side Drive

The circuit in Figure 1 shows a switch, connected to the high (ungrounded) side of the battery, in series with the solenoid coil and the grounded resistive shunt. A reversed diode is connected across the coil to clamp (i.e., short-circuit) the inductive voltage generated by the coil when the current is turned *off*. Using a ground reference for the shunt allows an inexpensive op amp—with indifferent common-mode specifications—to be used in the electronic control unit (ECU) to measure the voltage across the shunt.
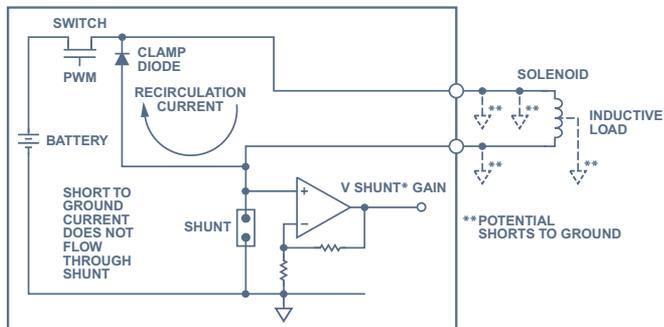
HIGH-SIDE DRIVE/LOW-SIDE SENSE
- LOWER COST AMPLIFIER
- HIGHER COST SWITCH
- HIGHER COST DRIVE FOR SWITCH
- SHORT-CIRCUIT CURRENT DOES NOT FLOW THROUGH SHUNT WHICH DOES NOT ALLOW FOR DIAGNOSTICS OF SHORT TO GROUND (SHOWN OUTSIDE THE ECU), OR SOLENOID CONDITION POTENTIALLY DAMAGING WIRING AND THE SWITCH.

Figure 1. Electronic control unit with high-side switching and low-side sensing.

When considering this approach, the designer must take into account these disadvantages:

1. The solenoid recirculating current is not included in the measurement, so this circuit provides an inaccurate measure of the average current through the solenoid coil. The solenoid recirculation current can be an aid to detecting solenoid health; if some of the windings have begun to short, the condition can be seen by measuring the passively controlled recirculation current.

2. Because the switch is on the high side, it is more expensive to buy and to drive. The PWM drive requires careful level translation between the logic output of the microcontroller and the gate.

3. Additional circuitry is needed to detect shorts to ground because the short-circuit currents do not flow through the shunt. Damage to the wiring and the FET can occur if shorts to ground (Figure 1) are not detected.

4. The measurement may be unstable because, in practice, *ground* is not the *ideal* universal connection, graphically rendered as a little inverted triangle. In the actual application, "ground" may not in fact be *ground*. Voltage drops caused by currents between the op-amp's ground and the shunt ground can cause significant errors.

High-Side Current Sensing with a Low-Side Switch

A better method of driving the solenoid is to use a switch that is referenced to ground (Figure 2), allowing the use of a less expensive, low-side switch.

Significantly better diagnostics are possible because the solenoid recirculation current is included in the measurement. In addition, the drive is less expensive, because it is not necessary to perform level translation to the gate.
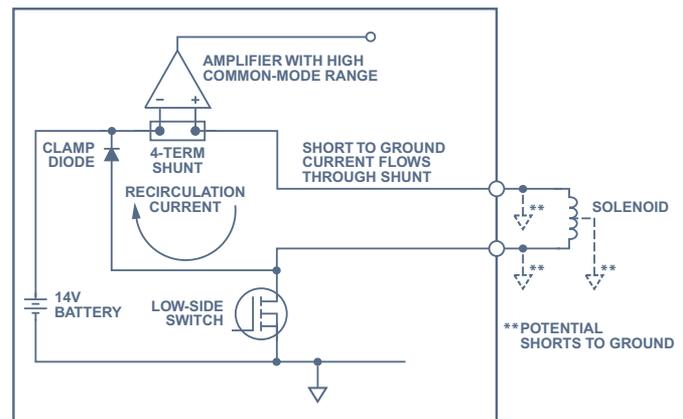
LOW-SIDE DRIVE/HIGH-SIDE SENSE
- LOWER COST SWITCH
- LOWER COST DRIVE FOR SWITCH BECAUSE THE GATE IS GROUND REFERENCED
- NEED TO USE A DIFFERENTIAL AMPLIFIER WITH COMMON-MODE RANGE THAT EXTENDS ABOVE THE BATTERY
- ALLOWS DIAGNOSTICS AND PROTECTION FOR SHORTS TO GROUND

Figure 2. Electronic control unit with low-side switching and high-side sensing.

However, the amplifier must have high, common-mode rejection, and it must be able to stand off significant common-mode voltage (CMV). The voltage level at the shunt in this example varies from battery voltage to battery-voltage-plus-a-diode-drop. Here's the explanation: When the switch is closed, the common-mode voltage level at the shunt remains at the low impedance battery voltage. When the switch is opened, the voltage across the solenoid reverses because of the solenoid's inductance, and causes the common-mode voltage level to include the clamping diode drop—while the transient current flows—before settling to the battery voltage.

An important benefit of this drive method is that it allows detection of shorts to ground, because the high-side current flows through the shunt—as seen in Figure 2.

A key concern when using this current sensing method is that the high side of the battery is always connected to the solenoid. This could allow the solenoid to switch unexpectedly if there is an intermittent short to ground. Also, the continuous presence of the voltage at the solenoid could cause excessive corrosion over time.

High-Side Current Sensing with a High-Side Switch

A configuration that minimizes the possibility of unexpected solenoid activation and excessive corrosion is shown in Figure 3, where both the switch and the shunt are connected on the high side. This removes the battery voltage from the solenoid when the switch is *off*, preventing damage from potential shorts to ground, and allows the recirculating current to be included in the measurement. The battery voltage is removed from the load when the switch is open, so corrosive effects caused by the voltage differential are eliminated.
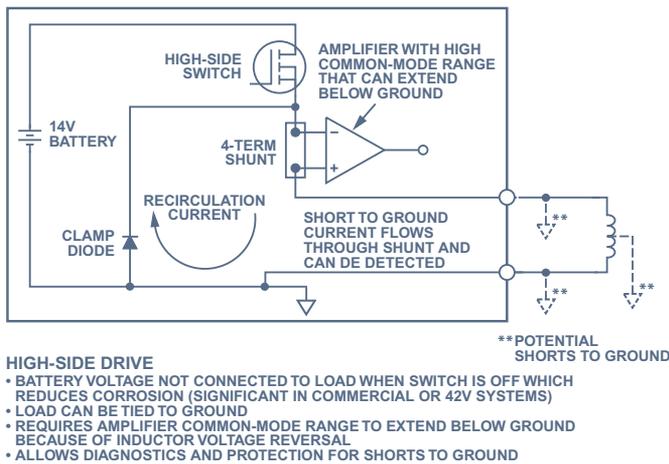
Figure 3. Electronic control unit with low-side solenoid and high-side switching and sensing.

In this case, however, the voltage reversal across the solenoid when the switch is opened will cause a much wider swing of common-mode voltage, from battery high-side voltage to one diode drop below ground (the reverse voltage is limited by the clamping diode). The amplifier used in this application must thus be able to provide accurate measurement of the shunt voltage (current), ignoring the large, rapid swing of common-mode voltage when the switch goes *off*.

As with the low-side switching, high-side sensing configuration (Figure 2), it is possible to measure shorts to ground, because all of the solenoid current from the high side flows through the shunt, as seen in Figure 3.

A Simple High-Side Current Measurement Circuit
Fortunately, the AD8200 single-supply difference amplifier, with all the desirable properties for this application—*complete in a single IC package*—is available from Analog Devices. Figure 4 shows an example of the AD8200 applied in an ECU to measure current on the high side in this type of application. Here, the AD8200 is used to amplify and *filter* the small, differential voltage from the shunt, while rejecting the large common-mode swings mentioned above. The AD8200 can be used in any of the configurations shown earlier.
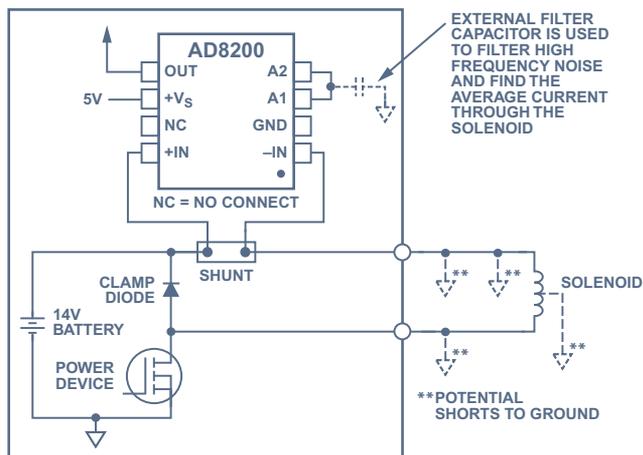

Figure 4. Electronic control unit, using the AD8200, with low-side solenoid and high-side switching and sensing.

The AD8200 uses a single +5 V supply and has an input common-mode voltage range extending from –2 V to +24 V, with load dump to +44 V. If higher common-mode range is required, use of another member of the AD8200 family is recommended—for

example, the AD8205, with a CMV range of –2 V to +65 V and a gain of 50; or the AD8206 with a CMV range of –2 V to +65 V and a gain of 20 (the same gain as the AD8200).
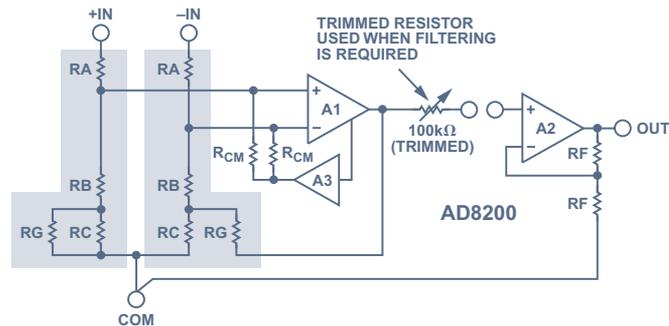

Figure 5. Functional block diagram of the AD8200.

Figure 5 is a functional block diagram of the internal wiring of the AD8200. Before designing a differential amplifier using an inexpensive op-amp and some external resistors, consider that achieving the performance required to measure solenoid current accurately enough for a control application requires a circuit built with resistors that are precisely matched to within 0.01%. The AD8200 has internal laser-trimmed resistors that allow for this level of precise operation when handling both ac and dc voltages. Typical offset- and gain drift in the SOIC package are 6 μV/°C and 10 ppm/°C, respectively. The device also provides a minimum, common-mode rejection of 80 dB from dc to 10 kHz.

Besides its availability in the SOIC package, the AD8200 is also available in die form. Both package options are specified over wide temperature ranges, making the AD8200 well suited for use in many automotive and industrial platforms. The SOIC package is specified for –40°C to +125°C and the die is specified from –40°C to +150°C.

The AD8200 also features an externally accessible 100-kΩ resistor at the output of the preamplifier, which can be used with external capacitance for low-pass filter applications, and with external resistors for establishing gains other than the preset gain of 20.

APPENDIX
Mechanical Transmission Control
The older method of controlling transmission shift points involved complex, speed-dependent hydraulic circuits. Shifting was done through the use of changes in hydraulic pressure in a complex valve body. The hydraulic pressure was modulated by a governor attached to the output shaft. Centrifugal force moved the governor, releasing transmission oil and increasing the pressure in the valve body. The method of adapting to changing driving conditions typically consisted of forcing the transmission to downshift under heavy acceleration or loading with mechanical actuators.

When the driver needed more acceleration, the requirement was typically transmitted via a down-shift mechanism, consisting of a rod running from the throttle control in the engine compartment to the side of the transmission. The rod moved a lever, closing off a series of channels in the throttle body. This forced the transmission to downshift under heavy acceleration until, at speed, the governor overrode the down-shift mechanism.

Adapting to changes in load was accomplished using a vacuum modulator. With increasing load on the engine, the vacuum change caused a rod to slide in or out of the valve body, changing the transmission shift point and shift speed. While these methods of controlling shift points and shift smoothness worked, there was little that could be done to adjust these parameters to more variable conditions because of the characteristics of the mechanical system used to control them. ▶