Technical Article
Current-sensing Dynamics in Automotive Solenoids

TEXAS INSTRUMENTS

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During my first visit to the U.S., my brother and I drove from New York City to Columbus, Ohio. Although the 650-KM (400-mile) journey was long, our car's automatic transmission and cruise control made the trip more comfortable. The effectiveness of an automatic transmission and cruise control relies on the precise control of proportional solenoids and motors, which is made possible with accurate current measurement.

Proportional solenoids convert electrical signals into a proportional mechanical force, which allows variance in armature position and force relative to the level of current. Proportional solenoids are used in automotive applications such as automatic transmissions, fuel injection systems, pistons and valves to accurately control position or flow. Controlling proportional solenoids precisely is highly dependent on the accuracy of the position estimation over the automotive temperature range. In general, measurement is used to provide position for proportional solenoids.

As shown in Figure 1, a shunt resistor is inserted in between the switch and the solenoid. The low-ohmic shunt is inserted in such a way to create a low resistance path as well as safely measure and accommodate recirculation current flows. An amplifier in a differential configuration or current sense amplifier is connected to the shunt to measure the current.
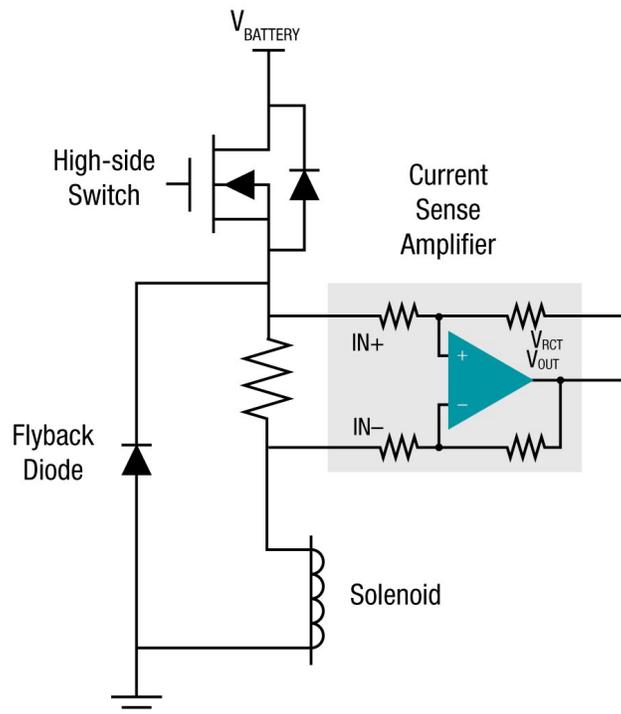

Figure 1. Solenoid current measurement

A pulse width modulation (PWM) signal operates the high-side switch. When the PWM is high, the battery connects to the solenoid and current flows. When the PWM is low, the battery disconnects from the solenoid and recirculation current flows through the flyback diode.

The control of the PWM frequency and duty-cycle percentage determines the resulting average current in the solenoid, which in turn controls the force applied to the actuator.

Sensing accuracy

Nominal current ranges for solenoids vary from device to device. Because of differing current range needs, current sense amplifier selection for these types of systems is critical as the necessary precise movement of the entire solenoid system depends on the accuracy of the current measurement.

Solenoid current sensors can be designed with external shunts or integrated shunt devices depending on the accuracy requirement. Each has their own advantages. Table 1 **and** Table 2 summarize the differences and benefits of these two architectures.

Table 1. Differences for external and internal shunt devices.

	External shunt devices	Integrated shunt devices
Suitability	Lower-current solenoids, because it is possible to interface with a higher-value external shunt resistor	Higher-current solenoids, as the integrated shunt is 2 mΩ. Choose based on your accuracy requirement.
Differential configuration register placement	Integrated	Integrated
Temperature drift	Shunt tolerances independent of device tolerance specifications, with considerable drift over the temperature range	Shunt tolerances included in device tolerance specifications, implying less drift over the temperature range
Resistor quality	• External resistor enables system-level flexibility on maximum current rating • Attention to PCB traces to shunt for measurement accuracy • Total system error dominated by shunt quality • Fixed ±15-A maximum current rating • Ease of design • Factory-trimmed to guarantee overall system reduction • Integrated 3-nH low inductive shunt with low drift over temperature (15 ppm/°C) • 0.1% integrated 2-mΩ shunt resistor	• Fixed ±15-A maximum current rating • Ease of design • Factory-trimmed to guarantee overall system reduction • Integrated 3-nH low inductive shunt with low drift over temperature (15 ppm/°C) • 0.1% integrated 2-mΩ shunt resistor
Kelvin connection	External	Internal
Common-mode voltage	-4 V to 80 V	-4 V to 80 V

Table 2. Benefits of external and integrated shunt devices.

	External shunt devices	Integrated shunt devices
Benefits	• High common-mode rejection ratio enables direct in-line motor current sensing • Simplifies system design, enabling faster time to market • Flexibility for various current ranges and also easily manageable • High common-mode rejection ratio enables direct in-line motor current sensing • Simplifies system design, enabling faster time to market • High accuracy minimizes system margins and potentially eliminates system-level calibration • Low inductance reduces PWM spikes and improves measurement accuracy _____ • Novel approach to handling high common-mode voltage transients • Instead of using a high bandwidth amplifier, can implement a circuit to filter these input transitions from reaching the output buffer • Novel approach to handling high common-mode voltage transients • Instead of using a high bandwidth amplifier, can implement a circuit to filter these input transitions from reaching the output buffer	• High common-mode rejection ratio enables direct in-line motor current sensing • Simplifies system design, enabling faster time to market • High accuracy minimizes system margins and potentially eliminates system-level calibration • Low inductance reduces PWM spikes and improves measurement accuracy _____ • Novel approach to handling high common-mode voltage transients • Instead of using a high bandwidth amplifier, can implement a circuit to filter these input transitions from reaching the output buffer
Enhanced PWM rejection system-level benefit	• Substantially reduced "blanking time" • Accurate measurement at lower duty cycles • Substantially reduced "blanking time" • Accurate measurement at lower duty cycles	• Substantially reduced "blanking time" • Accurate measurement at lower duty cycles
Inclusion of flyback period in measurements.	Required wide common-mode range to accommodate the solenoid flyback period	Required wide common-mode range to accommodate the solenoid flyback period
Inductance	Low, in order to reduce voltage swings during state transitions	Low, in order to reduce voltage swings during state transitions
Price	Relatively lower price (excluding shunt price)	Moderately higher (including shunt price)
Relevant TI reference design	Reference Design for Automotive, Proportional-Solenoid Current Sensor	Automotive Proportional Solenoid Drive with Highly Accurate Current Sensor Reference Design

Figure 2 **and** Figure 3 shows the configurations of shunt for external and internal configurations. In Figure 2 shunt is external to the device (INA240-Q1) and in Figure 3 shunt is internal to the device (INA253-Q1).
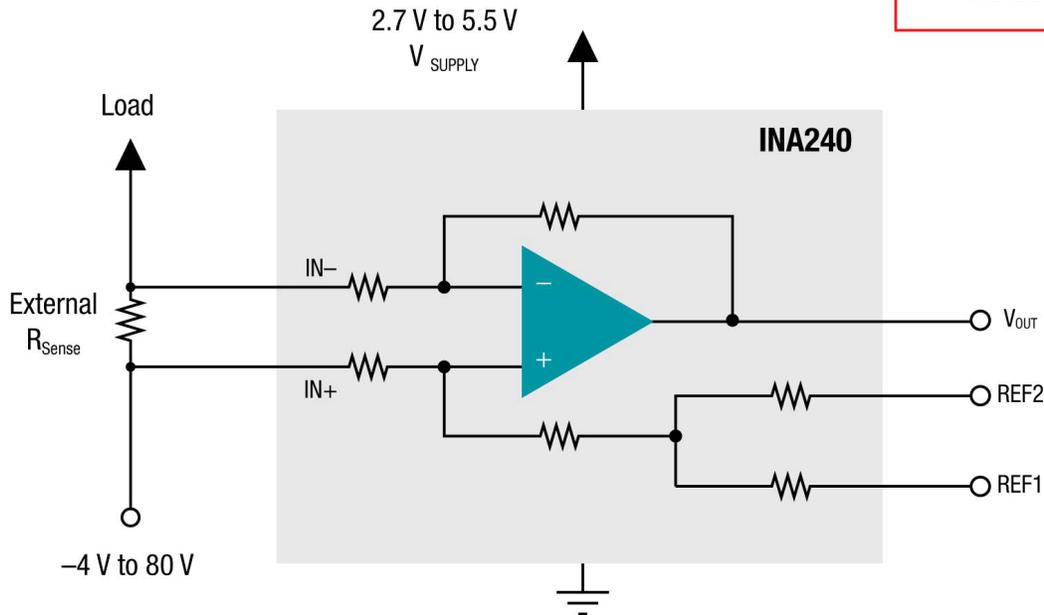
INA240

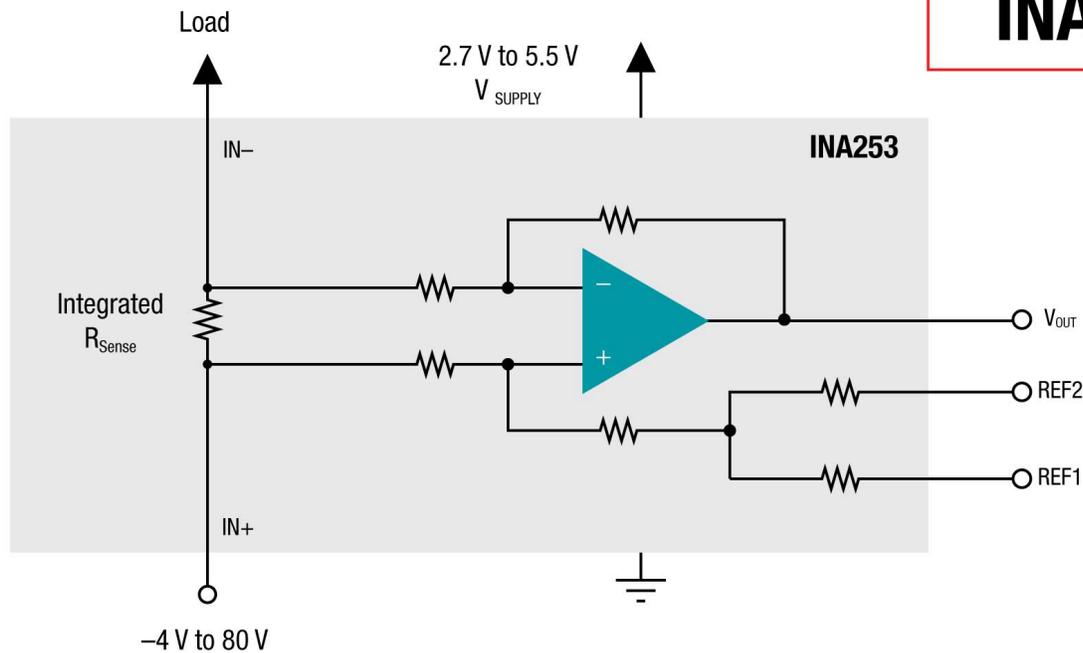**Figure 2. External shunt configuration with INA240**

INA253

Figure 3. Internal shunt configuration with INA253

Maintaining solenoid current sensing accuracy

The impedance of a solenoid comprises inductive and series resistive components. The series resistance of the coil (typically copper) has a high-temperature drift of 4,000 ppm/°C. This high drift value may correspond to a 40% accuracy reduction in solenoid motion control over a 100°C range.

Accuracy at lower current ranges is essential over the entire temperature range mainly because lower currents are noise prone and there is a more chance for the solenoid position inaccuracies. Smooth operation of hydraulic systems requires a minimum 2-mA resolution. Variations in this resolution cause solenoid position inaccuracies.

TI has two devices designed for solenoid current sensing applications:

- The INA240-Q1 enhances PWM rejection and has significantly lower offset and gain drifts over the temperature range, minimizing error at a 2-mA resolution.
- The INA253-Q1 is a low inductive 3-nH 2-mΩ integrated shunt with a drift at 15 ppm/°C. Placing the INA253-Q1 in series with the solenoid, the drift accuracy can decrease overall end-equipment system errors from 40% to 0.15%.

These devices have increased the effectiveness of our powertrain, motor-control circuits and automotive battery systems.

Conclusion

Automotive solenoids need higher accuracies to compensate for wider temperature ranges and increased drift as the temperature increases. Our current-shunt monitors enable accurate readings across the entirety of automotive temperature ranges.

Additional resources
- Check out the Automotive Shunt-Based ±500 A Precision Current Sensing Reference Design.
- Read Dan Harmon's contributed article, "Signal Chain Basics #128: Optimizing solenoid control with precision current measurement."

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