Mouser Electronics White Paper

Basics and Trade-offs of Resistor-Based Current Sensing

Resistor-Based Current Sensing: Simple in Concept, Challenging in Practice

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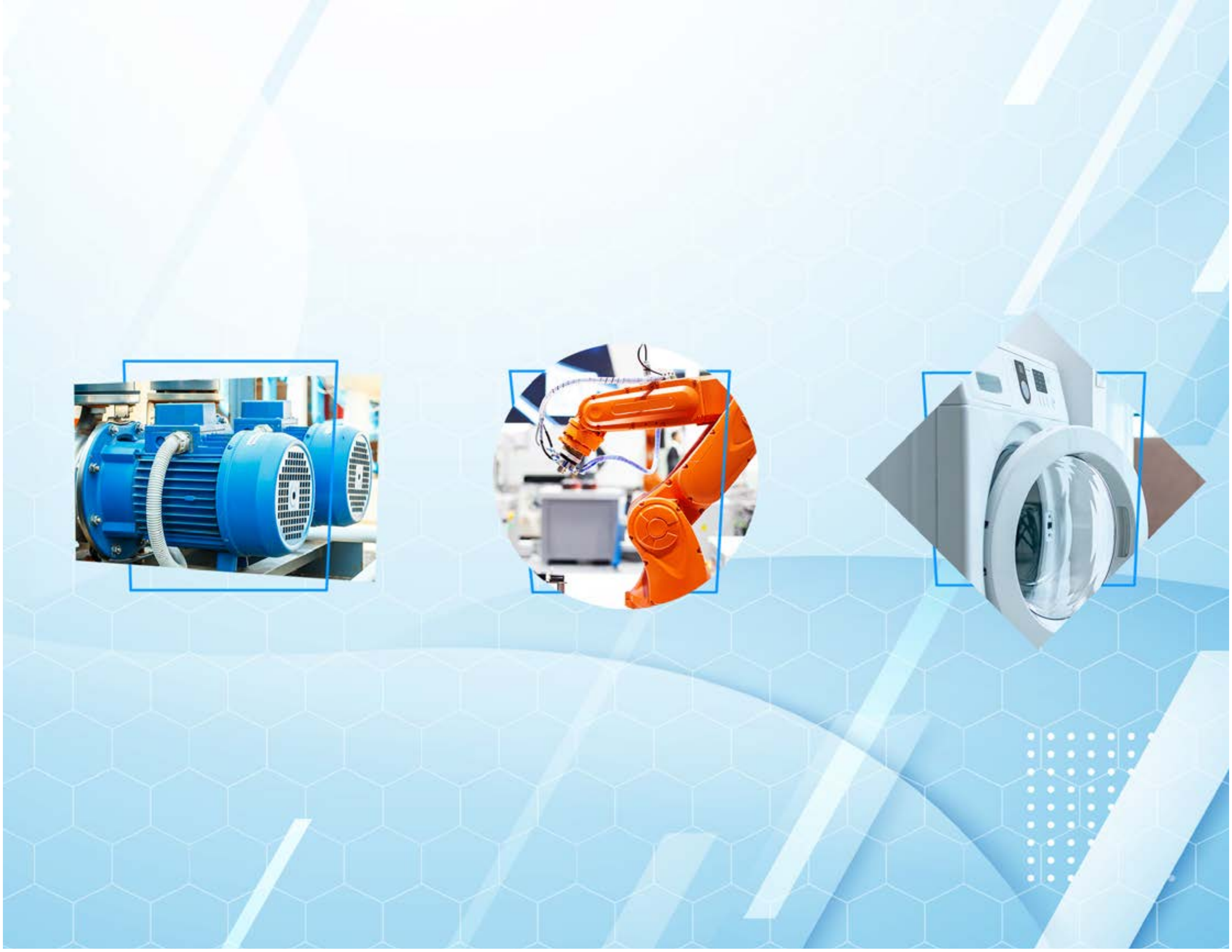

Measuring current at a load or within a critical circuit path is often an important system parameter, and it has become more so with the proliferation of smart, energy-saving motor controls and high-efficiency, fast-response power supplies. Knowing the current is essential to ensure crisp closed-loop performance as well as anticipate and respond to out-of-bound conditions.

Among the many ways to sense current is the use of a Hall-effect device, a discrete current-sensing coil, or a **current-sense resistor**. Each of these options has trade-offs in size, accuracy, cost, complexity, production flow, and overall compatibility with the system's physical constraints. For example, Hall-effect devices are somewhat sensitive to external magnetic interference and might have slower response times that can cause phase lag (loss of torque) in motor applications. In contrast, resistor-based sensing has no noticeable lag, long life stability, and lower cost than the Hall-effect in large volume. For these and many other reasons, the sense resistor is often the selected technique.

Note that for motors, it is possible to monitor performance using a shaft-mounted tachometer or encoder to sense rotor position and speed. Although this certainly works, the transducer must be mounted to the motor itself, which increases cost and adds to installation issues. However, by sensing only the current to the motor, it is possible in many cases to determine almost as much information as you would by monitoring the rotor directly, yet with a smaller, simpler, lower cost, and more reliable approach. In addition, sensing the current to the motor can actually reveal some aspects of system performance that a direct-rotor measurement cannot show.

It's Just Ohms Law: What Could be Simpler?

Here, we'll focus on issues associated with using a resistor for current sensing and measurement. The principle is simple: Insert a known resistor in a series with the wire carrying the current to be sensed and measure (sense) the voltage across that resistor. This analog voltage can be used directly in a feedback loop or digitized and sent to a microcontroller.

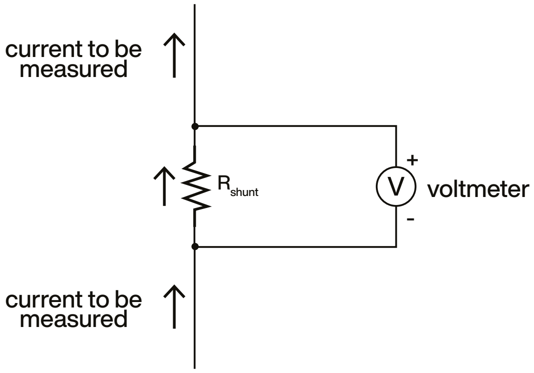

Figure 1: The basic principle of determining current using a resistor is deceptively simple: Use Ohm's law and a known resistor value, measure the voltage across the resistor, and you can determine the current. (Source: Electrical Engineering Stack Exchange)

The Ohms' law relationship (Figure 1) between the sensed voltage and the actual current is clear: I = V/R.

Nevertheless, issues and trade-offs are associated with using resistor-based current sensing. These are:

- High-side versus low-side sensing, and the associated amplifier electronics
- Determining the resistor value
- Selecting the right type of resistor
- The physical connection

Let's look at them in more detail:

High-side Versus Low-side Sensing, and Associated Amplifier Electronics

The sense resistor—often called a shunt resistor (but that is somewhat of a misnomer)—can be inserted in either the low side or the high side of the load. In low-side sensing, the resistor is placed between the load and "ground" (or, in many cases, circuit "common"), as shown in Figure 2 below, which enables the associated voltage-sensing circuit to also be connected directly to ground.

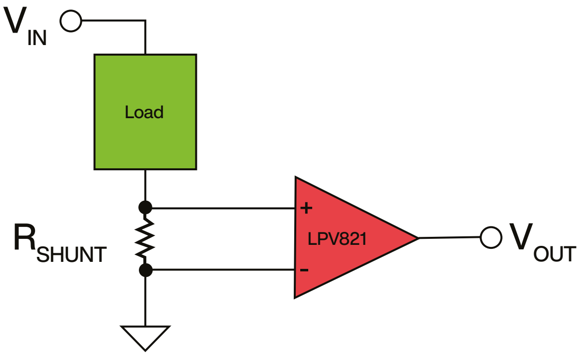

Figure 2: In low-side sensing, the resistor is inserted between the load and common (or ground), which simplifies the voltage-reading interface but also incurs system issues. (Source: Texas Instruments)

Although components in this topology are not subject to any high-voltage issues, it is often undesirable and even unacceptable, for two reasons. First, doing so means the load itself is not connected to circuit common or ground, which is impractical for mechanical reasons in many installations; for example, having an ungrounded starter motor in a car and insulating it from the chassis is a design and mounting challenge. Second, doing so also mandates the need for a return wire that can carry the load current back to the source, rather than using the chassis. Finally, even if wiring and mounting are not considerations, placing any resistance between the load and ground (common) negatively affects the control-loop dynamics and control. In general, ungrounded loads require special attention in overall circuit topology and physical installation.

The alternative to a low-side sensing solution is to use high-side sensing, with the resistor instead placed between the power rail and the load (Figure 3). This eliminates the problems attributed to un-grounding the load, but brings new issues that must be addressed by the voltage-sensing interface amplifier.

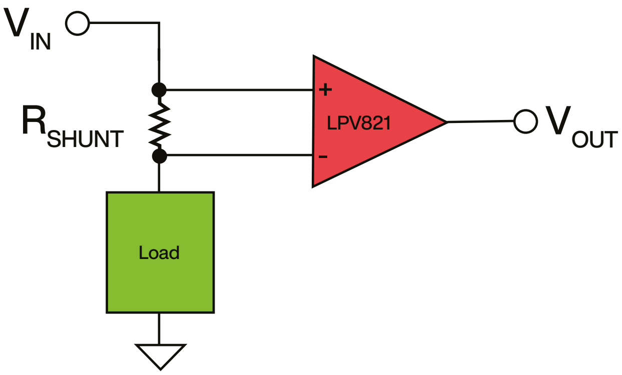

Figure 3: High-side sensing places the resistor between the current source or rail and the load it is sullying; it has technical issues but avoids the negative effects of disrupting the load relationship with common (or ground). (Source: Texas Instruments)

A standard operational amplifier (op amp) would normally be the interface component for sensing and amplifying the voltage across the sense resistor. However, a standard op amp requires that the non-inverting input be connected to the circuit common or ground, but this is not allowed with high-side sensing, as it would short-circuit the high-side arrangement to ground.

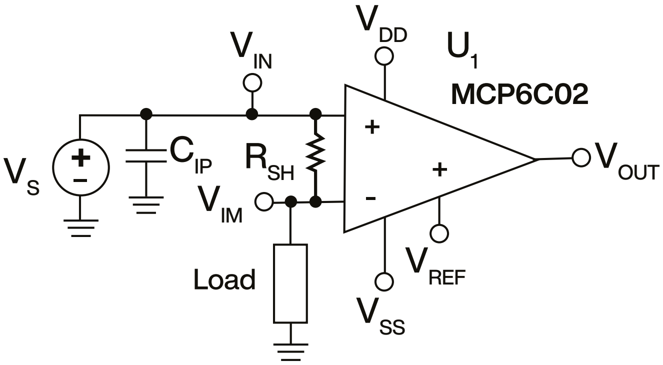

Figure 4: The Microchip Technology MCP6C02 is a high-side current-sense amplifier that offers three preset gain levels along with CMV up to +65V and can monitor bidirectional voltages and thus current flows. (Source: Microchip Technology)

Instead, an op amp called a difference (or differential) amplifier must be used. In this amplifier, neither of the two inputs is ground-referenced. Instead, this device amplified the difference between its two inputs, thus measuring the voltage across the non-grounded sense resistor.

In addition to the usual op amp specifications such as gain accuracy, offset voltage, bias voltage, various temperature coefficients, another key specification is associated with these amplifiers: maximum common mode voltage (CMV) they can tolerate. This is the voltage above ground that the two inputs "see" and which is common to both of them; it is usually equal to or just below the supply-rail value.

A good example of a high-side current-sense amplifier is the MCP6C02 from Microchip Technology, which is available with preset gain values of 20V/V, 50V/V and 100V/V (Figure 4), and with a common-mode input range of +3V to +65V. As an added feature, its differential-mode input supports bidirectional sensing, needed in bipolar (dual-supply) applications where the current can flow in either direction. Further, the innovative Zero-Drift

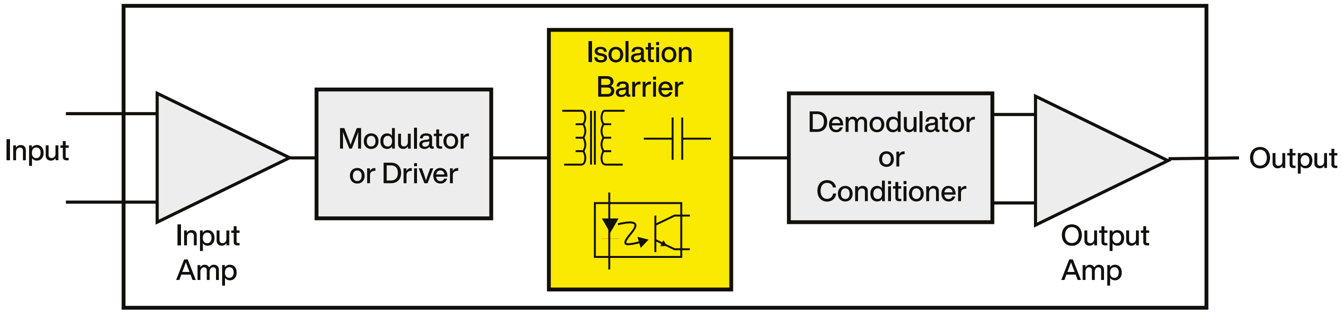

Figure 5: Galvanic isolation allows sensing of voltage but without an ohmic path between the sensor and front-end amplifier; it provides many circuit and system benefits but at an additional component cost. (Source: SlidePlayer.com Inc.)

architecture yields very low input errors, which allow a design to use shunt resistors of lower value (and lower power dissipation).

In summary, low-side resistor-based current sensing is simpler, but also incurs the ungrounded-load dilemma; high-side sensing avoids that problem but requires the appropriate amplifier. Most current-sensing implementations use high-side sensing with few exceptions

In general, if the rail voltage is higher than the CMV rating supported by standard IC processes (typically, up to about 100V), then more complicated approaches to a high CMV interface are needed. An alternate approach that is used when CMV is high (and for other reasons) is galvanic isolation between the sensing amplifier input and output (Figure 5). This means no ohmic path between the two analog sections, yet it appears like a non-isolated amplifier and brings other beneficial features as well.

Galvanic isolation greatly improves system performance in many ways. It eliminates ground loops and associated issues; simplifies subsequent circuitry; eases or eliminates safety-related layout and wiring requirements on clearance and creepage dimensions; adds an electrical safety barrier between any high voltage and the rest of the system; and is often mandated by safety and regulatory standards in many applications. Isolation can be implemented using magnetic, optical, capacitive, or even RF techniques.

Determining the Resistor Value

Ideally, the sensing-resistor value should be relatively large so the resultant voltage drop will also be large, thus minimizing effects of circuit and system noise on the sensed voltage, as well as maximizing its dynamic range. However, a larger value at a given current also means less voltage—and thus less available power—for the load because of IR drop. There will also be wasted power in the resistor because of I2R dissipation, self-heating, and added thermal load. The back-and-forth tug between choosing a larger and smaller resistor value is a classic example of an engineering situation involving trade-offs and compromises.

In practice, as a first-step “rule of thumb” it is generally desirable to keep the maximum voltage across the sensing resistor to 100mV or below. As a result, the corresponding resistor values are in the tens-of-milliohms range and even lower. Sense resistors are widely available in these small values; even one-milliohm and lower resistors are standard catalog offerings. At these low values, even the resistance of the ohmic contacts of the sensing circuitry is a factor in the calculations.

Selecting the Right Type of Resistor

The dilemma of resistor selection does not end with determining a value that balances the trade-offs. First, the resistor dissipation creates self-heating, which means the selected resistor type must have a suitable power rating, and it must be derated at higher temperatures.

A typical PC board, even a highly digital one, is typically populated with dozens and even hundreds of resistors, many in the 1kΩ to 100kΩ range for functions such as open-lead pull-ups, termination, transient snubbing, and many other roles. Any self-heating because of I2R dissipation will cause the resistor to drift from its nominal value. How much it drifts depends on the material and construction of the sense resistor. A standard low-cost chip resistor has a temperature coefficient of resistance (TCR) of about ±500 ppm/°C (equal to 0.05%/°C). Any self-heating would cause a significant amount of change in the resistor value and thus error in the calculated current.

To counter this error source, resistors fabricated for current sensing used special material and construction techniques and are available with TCRs from ±100 ppm/°C down to about ±20 ppm/°C; precision-performance units are also offered (at a much higher cost) down to ±1 ppm/°C.

One commonly used tactic for reducing the temperature rise because of self-heating is to use a larger wattage version, which will be less affected by self-heating; but these, too, have a somewhat higher component cost and larger footprint. The designer must do a careful analysis of the current, the dissipation, the effects of TCR, and any derating needed for long-term reliability and performance.

In some cases, it is possible to use a small piece of copper wire or PC-board track to get a milliohm-valued sense resistor at nearly zero cost. However, this requires tight control over board copper thickness and fabrication, and should be considered only if the current level, and thus self-heating dissipation, is very low. The reason is that the TCR of copper is around 4000 ppm/°C (0.4%/°C), which is on orders of magnitude inferior to a low-TCR sense resistor.

Vishay WSLF Power Metal Strip® Resistors

To meet the challenging requirements on higher current sense resistors, vendors have engineered specialized units that target these situations. For example, specialty resistors such as those in the **Vishay WSLF Power Metal Strip® Resistors** series look like innocuous metal strips (Figure 6), but they are actually fabricated

Figure 6: Sub-milliohm-range, multi-watt current sense resistors such as these in the Vishay WSLF Power Metal Strip® Resistor series are carefully engineered with respect to electrical, material, and mechanical characteristics to provide precision performance along with a low-temperature coefficient and moderate power-handling capability. (Source: Vishay)

of solid metal nickel-chrome, manganese-copper, or manganese-copper-tin alloy resistive elements with low TCR (<20 ppm/°C).

These SMT devices are available with extremely low-resistance values as low as 0.0003□ (0.3m) and, depending on ohm value, they can dissipate between 4W to 6W at 70°C and 2W to 3W at 100°C. In addition, they feature very low inductance (<2nH) and meet the stringent automotive AEC-Q200 qualification. Finally, they offer superior pulse-withstanding tolerance for locked-rotor conditions, which do occur. The Vishay website provides a number of design tools to assist design engineers, including the **Vishay SMD Power Metal Strip® Pulse Calculator**. This design tool calculates and creates a custom report detailing the pulse capability of a selected Power Metal Strip current sense resistor.

The Physical Connection

At very low current levels, the physical size of the current-sense resistor is about the same as other resistors. But physically larger resistors are needed as the wattage rating increases, and this has an impact on both PC board layout–assuming the resistor is board-mounted–and the thermal situation of both the resistor and its surroundings. For the higher rated resistors, placement and mounting becomes an issue of concern as PC-board surface mounting might not be an option and real estate and thermal issues increase significantly. Larger units might even need mounting brackets or hold-downs to keep motion and vibration effects down to an acceptable minimum.

The arrangement of the current-carrying leads and the voltage-sense leads constitute a four-wire Kelvin connection, and the physical difficulty of making the "simple" electrical connections shouldn't be overlooked. When wires carry tens or even hundreds of amps, the connections between those wires and the resistor's termination takes careful planning and larger, more rugged surfaces, will be required including screws and clamps. Just think of the typical internal-combustion car battery, which must deliver over 100A when cranking to start the car, and do so from a modest 12V battery: Even 100mΩ contact resistance at the battery terminal translates to a supply loss of 1.2V (10 percent of nominal), and that is in a scenario where there isn't much voltage headroom.

In addition, even though the sensed voltage is low, the common-mode voltage might not be low, and the connections might be carrying high currents, so safety and access issues can affect cabling, routing, possible short circuits, and accessibility. Further, the designer must plan where and how to connect the relatively thin-gauge voltage-sensing wires to the large contacts that also carry the higher load current. Resistance of the sensing-wire contacts might look like resistance, which is part of the sense resistor itself, and so the I = V/R calculations need to factor in this additional resistance; even the TCR of any contacts can also be an issue in higher accuracy situations.

Also, consider the subtle Seebeck effect (the basis for thermocouples), which occurs when dissimilar metals contact each other. Because of this effect, a small and error-inducing electromagnetic field (EMF) voltage will be developed at the junction of the sense resistor and connecting wiring. For this reason, high-performance sense resistors such as those in the Vishay WSLF family cited previously are designed and fabricated to develop low-thermal EMF of less than 3μV/°C.

Conclusion

Using a resistor for current sensing is an example of the challenges of going from a solution that is very simple in principle, to one that works, works well, and works over the range of expected operating conditions of the application, as long as the real-world issues and trade-offs are understood and resolved. Fortunately, it is also a solution that is used extensively, so many of the issues can be addressed by leveraging the experience of application engineers at the resistor suppliers or experts in high-current sensing.