Understand low-side vs. high-side current sensing

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Power management in today's electronic systems optimizes system efficiency via effective power distribution. A critical aspect of this management is current sensing, which not only helps to maintain the desired power levels, but also maintains the health of the electronic system by providing servo regulation, while also preventing circuit faults and over-discharged batteries.

Two basic schemes are available for sensing electric current. You can either measure the magnetic field around a current-carrying conductor, or insert a small resistor in the current path and measure the voltage drop across it. The first approach doesn't intrude or introduce insertion loss, but it's relatively expensive, and also prone to the effects of nonlinearity and temperature-coefficient error. Thus, magnetic-field sensing is usually restricted to applications that can justify the higher cost associated with the prevention of insertion loss.

This article focuses on the resistive-sensing techniques made available by the semiconductor industry, which provide accurate and cost-effective measurements of DC current for various applications. Low-side and high-side sensing is explained, with examples that can aid designers in selecting an optimal approach for their applications.

Resistive sensing
Inserting a low-valued sense resistor in series with a current path produces a small voltage drop, which can then be amplified to serve as an output signal proportional to current. Depending on the application environment and the sense resistor's placement, however, this technique can create various challenges for the sense amplifier.

If the sense resistor is placed between the load and the circuit ground, for example, the resulting voltage drop can be amplified using a simple op amp (**Figure 1, right side**). Called low-side current sensing, this approach differs from high-side sensing, in which the sense resistor is placed between the supply and the load (**Figure 1, left side**).

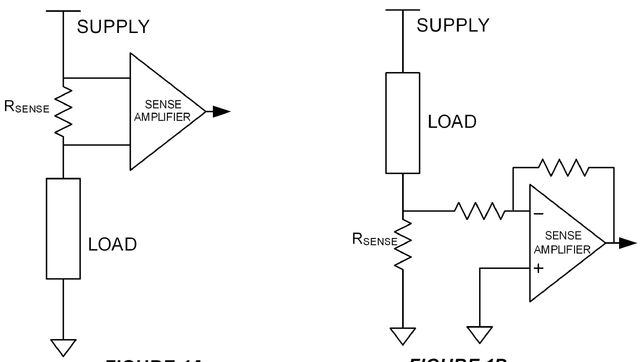

FIGURE 1A **FIGURE 1B**

Figure 1: These simplified diagrams depict a basic high-side sensing circuit (a) and a basic low-side sensing circuit (b).
(Click on image to enlarge)

The value of the sense resistor should be as low as possible to keep power dissipation in check, but high enough to generate a voltage detectable by the sense amplifier, within the accuracy desired. Note that this differentially sensed signal across the sense resistor rides on a common-mode voltage, which for low-side sensing is close to ground (0V), but for high-side sensing is close to the supply voltage. The input common mode range for the measuring amplifier should thus include ground for the low side, and the supply voltage for the high side.

Because the common-mode voltage for low-side sensing is close to ground, the current-sense voltage can be amplified by a low-cost, low-voltage op amp. Low-side current sensing is simple and inexpensive, but many applications cannot tolerate the ground-path disturbance introduced by the sense resistor. Higher load currents can aggravate the problem, because one block in the system, with its ground level shifted by low-side current sensing, may be required to talk to other blocks whose ground potential is unchanged.

To better understand this problem, consider a "smart battery" charger employing low-side current sensing (**Figure 2**), for which the output of an AC-to-DC converter connects to a "2-wire-based" smart battery.

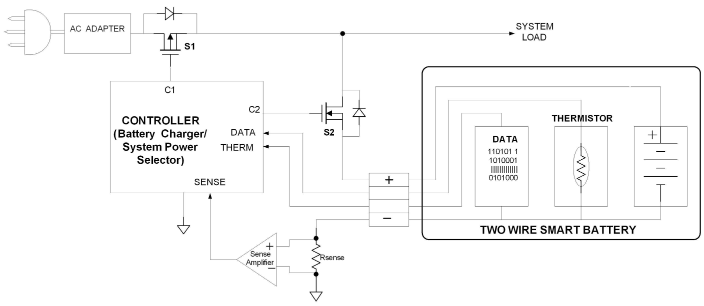

Figure 2: This "smart battery" charger employs low-side current sensing.
(Click on image to enlarge)

Such batteries usually employ a single wire for transferring the battery-specific information that indicates battery health. They also have a wire for temperature measurements, kept separate from the negative and positive terminals for safety reasons. For sensing battery temperature, the battery usually includes a thermistor that provides a proportional output with respect to the battery's negative pin.

For low-side sensing, you insert the sense resistor as shown at the bottom of Figure 2. The sense voltage produced by battery current is amplified and fed to the controller, which takes the action necessary to regulate power flow. As the sense voltage varies with battery current, it varies the voltage at the negative pin of the battery, which in turn causes the temperature output to become inaccurate because it uses the negative terminal as a reference.

Another major disadvantage of low-side sensing is that short-circuit currents resulting from accidental shorts between the battery and ground go undetected. In the circuit of Figure 2, a short between the positive supply and ground could draw currents large enough to damage the MOS switch (S1). Despite such issues, however, the simplicity and low cost of low-side sensing makes it attractive for applications in which short-circuit protection isn't necessary, and where ground disturbances can be tolerated.

Why high-side sensing?

High-side current sensing (Figure 1b) is accomplished by placing the sense resistor on the high side, between the supply voltage and load. Not only does this placement eliminate the ground disturbances found in low-side sensing, it also allows the detection of accidental battery shorts to system ground.

High-side sensing, however, demands that the sense amplifier handle a common-mode voltage that is close to the supply voltage. This common-mode voltage can vary from the level required in monitoring a processor core voltage (~1V), to the hundreds of volts found in industrial, automotive, and telecom applications. Examples include the battery voltage of a typical notebook computer (17 to 20V), automotive applications powered by 12V, 24V, or 48V batteries, 48V telecom applications, high-voltage motor-control applications, current sensing for avalanche photodiodes and PIN diodes, and high-voltage LED backlights. Thus, an important aspect of high-side current sensing is the sense amplifier's ability to handle large common-mode voltages.

Traditional high-side current-sense amplifier

For typical low-voltage applications operating with a 5V supply, the high-side sense amplifier can be a simple instrumentation amplifier (IA). Depending on the IA architecture, however, there can be restrictions such as a limited input common-mode range. IAs also tend to be expensive and at higher common-mode voltages, a low-voltage IA doesn't work at all. Thus, the amplifier required for high-voltage, high-side current sensing appears to be a design challenge.

An apparently straightforward solution to this problem is to scale down the high-side common-mode voltage using a simple resistive divider, so it falls within the input common-mode range of the sensing op amp. This approach, however, may prove not only to be bulky and expensive, but as explained below it can also fail to give accurate results.

Consider, for example, a 100mV sense voltage generated across a sense resistor that rides on a common-mode voltage of 10V. The desired output corresponding to the 100mV full-scale sense voltage is 2.5V, with a worst-case accuracy specification of 1%.

Let's say the 10V common-mode voltage is scaled down by a factor of 10 using the simple resistor divider shown in **Figure 3**.

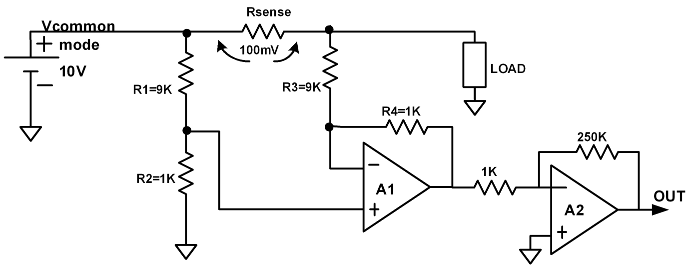

Figure 3: Circuitry as shown implements traditional high-side current sensing. (Click on image to enlarge)

Op amp A1, configured as a difference amplifier, easily handles the common-mode voltage of 1V. But Vsense (100mV) has also been scaled by the same factor, giving a sense voltage of only 10mV at the inputs of difference amplifier A1. To provide a full-scale level of 2.5V as required, you must introduce the additional amplifier A2, configured with a gain of 250.

Note that the input offset voltage of A1 appears at its output with no attenuation, while that appearing at the input of A2 is amplified with a gain of 250. Because these offset voltages are uncorrelated, they can be combined at the input of A2 as a root-sum-of-squares (RSS), to give the equivalent offset voltage. Assuming both op amps have 1mV of input offset voltage, the equivalent offset is:

$$(V_{OS\text{-}EQ})^2 = (V_{OS\_A1})^2 + (V_{OS\_A2})^2$$

where V_{OS_A1} and V_{OS_A2} are the input offset voltages of A1 and A2.

$$(V_{OS\text{-}EQ}) = \sqrt{(1mV)^2 + (1mV)^2} = 1.4mV.$$

Thus, the above configuration could give an error voltage of:

250(1.4mV) = 350mV

at the output of A2, due to input offset alone. Offset voltage of the op amp would then contribute a system error of 14%.

Effects of resistor-ratio mismatch on CMRR
The second major source of error stems from the tolerances associated with the resistive arms of amplifier A1. The CMRR of A1 depends strongly on the ratio of the resistive gain-setting arms R2/R1 and R4/R3. Even a 1% difference in the ratios of resistances in the two arms produces an output common-mode gain of 90µV/V.

Using resistors with 1% tolerance, the arms ratio can vary as much as ±2%, which can translate to a common-mode voltage error of 3.6mV/V under worst-case conditions. Thus, an input common-mode change of 10V can produce as much as 36mV of error at the A1 output (for a 1% variation in the resistive arms the error is 0.9mV). An error of 36mV is clearly unacceptable, because it causes A2 with its gain of 250 to saturate! Even a 1% variation in the resistive arm ratios produces an amplified error voltage of 0.9mV(250) = 225mV.

Total error
Total error is the RSS combination of A1 input offset voltage, A2 input offset voltage, and the error voltage due to resistor tolerances. As explained above, a 1% tolerance in the resistors plus a common-mode variation of 10V could by itself introduce a worst-case error of 36mV, which in turn saturates A2. Assuming the ratio between resistive arms R2/R1 and R4/R3 varies by just 1%, the output error could be as high as 0.9mV. Thus the total RSS input error voltage would be:

$$(V_{TOTAL\_OS})^2 = (V_{OS\_A1})^2 + (V_{OS\_A2})^2 + (V_{OS\_MISMATCH})^2,$$

where V_{OS_A1} and V_{OS_A2} are the input offset voltages of A1 and A2, and $V_{OS\_MISMATCH}$ is the input error voltage due to the 1% variation in resistive arm ratio:

$$V_{TOTAL\_OS} = \sqrt{(1mV)^2 + 1mV)^2 + 0.9mV)^2} = 1.67mV.$$

Even if we neglect temperature variations, the total error due to offset voltage of amplifiers A1 and A2 plus a 1% mismatch in the resistive arms ratio could be as high as 1.67mV(250) = 417.5mV, which is 16.7% of the full-scale output. In other words, the 417.5mV error voltage would look like an input-offset error of 417.5mV/25 = 16.7mV, which is clearly unacceptable.

Total error can be reduced by using tighter-tolerance resistors (0.1%) or amplifiers with better offset-voltage specifications, or both. But, these measures further increase the cost of a system that already includes numerous components.

Note that the resistive dividers R4/R3 and R2/R1 provide a path to ground for supply currents even without a load. This low common-mode impedance to ground can be critical in battery-operated devices, where leakage in the resistive path can drain the batteries rapidly.

Dedicated high-side current-sense amplifiers
Thus, there is need for a device that not only senses voltage at higher common-mode voltages, but also has very good CMRR and a low input-offset voltage. The basic high-side current-sense amplifier (CSA) of **Figure 4** is commonly available as an integrated circuit, available in small packages to minimize board space. The high-voltage manufacturing process used to produce such ICs allows them to handle common-mode voltages as high as 80V and above, even when operating from supply voltages as low as 2.8V.

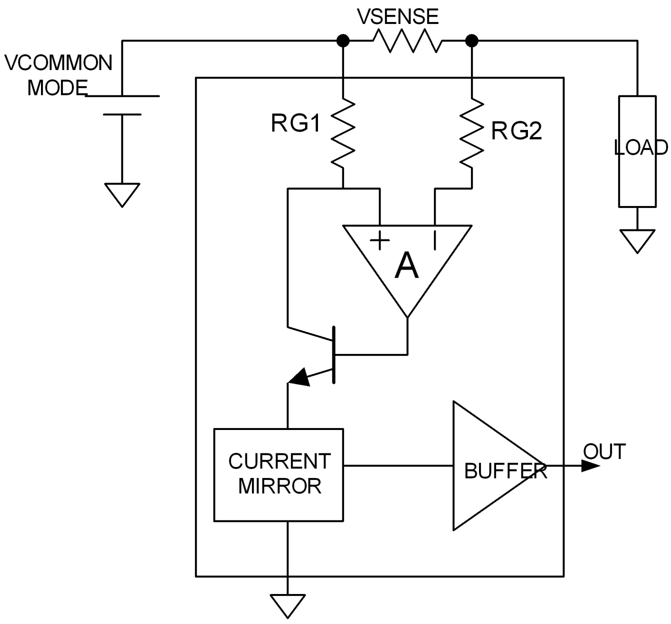

Figure 4: An integrated high-side current-sense amplifier includes these basic components (Click on image to enlarge)

Current flowing through the sense resistor in Figure 4 creates a small differential voltage that is forced across gain resistor RG1. This current (proportional to sense voltage) is mirrored and processed to deliver an output current referenced to ground, thereby accomplishing the desired level shift from the high side. This current output can be converted to voltage by passing it through a resistor or voltage buffer.

The high-side CSAs from Maxim meet the performance requirements for such applications: the chips have very high common-mode input impedance, minimal input offset voltage, sub-1% accuracy specifications, and a typical CMRR of 100dB. That combination delivers a cost-effective solution to the problems commonly found in traditional high-side CSAs. Additionally, the small package options (2.2mm × 2.4mm SC70, 3mm × 3mm SOTs, 1mm × 1.5mm USCPs, among others.) keep board space to a minimum.

These high-side amplifiers are suitable for low-cost current sensing in a multitude of applications, and each is optimized for a particular type of application. The MAX4372, MAX9928/29, and MAX9938, for example, are suitable for battery operated devices, while the MAX9937 and MAX4080 fit well in industrial systems. The MAX4069 and MAX9923 are good choices when extra-low offset current is needed. By eliminating the need for low-side current sensing, all of these ICs circumvent the problems of ground bounce and loss of short-circuit detection.

Author biography
Arpit Mehta is a strategic applications engineer for the Multimedia business unit at Maxim Integrated Products, Sunnyvale, CA, currently responsible for solving technical problems in the op-amp, comparator, and current-sense-amplifier product lines. Arpit graduated from San Jose State University, San Jose, CA, with a Master's Degree in Electrical Engineering.

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