High-Side, High Current Sensing Techniques

This application note discusses two new circuit techniques for measuring high-side current in power applications. Compared with the standard difference amplifier configuration, these new configurations offer considerably higher accuracy and gain-bandwidth.

Contents

1.   Introduction

There is a need in many applications to sense currents on the high-side rail of a power bus and translate it into a voltage with respect to ground, which is proportional to this current (see Figure 1). Typically, this voltage is fed into a microcontroller or used as an analog input to a switching power controller. This application note compares several methods of high-side current sensing, including two simple techniques that can be used to sense current on a high voltage rail using low voltage amplifiers.
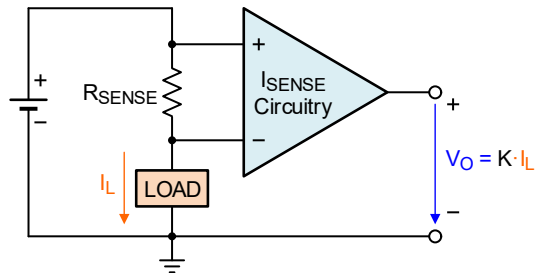

Figure 1. Simplified Block Diagram

There are various ways to sense high-side current, but no single solution. The ISL28006 (see Figure 2), is a compact solution for applications up to 28V. The fixed gain version requires almost no external components and the 450µV max offset over-temperature is excellent compared to similar products; however, some applications require lower offset for better precision or require sensing of a rail higher than 28V.
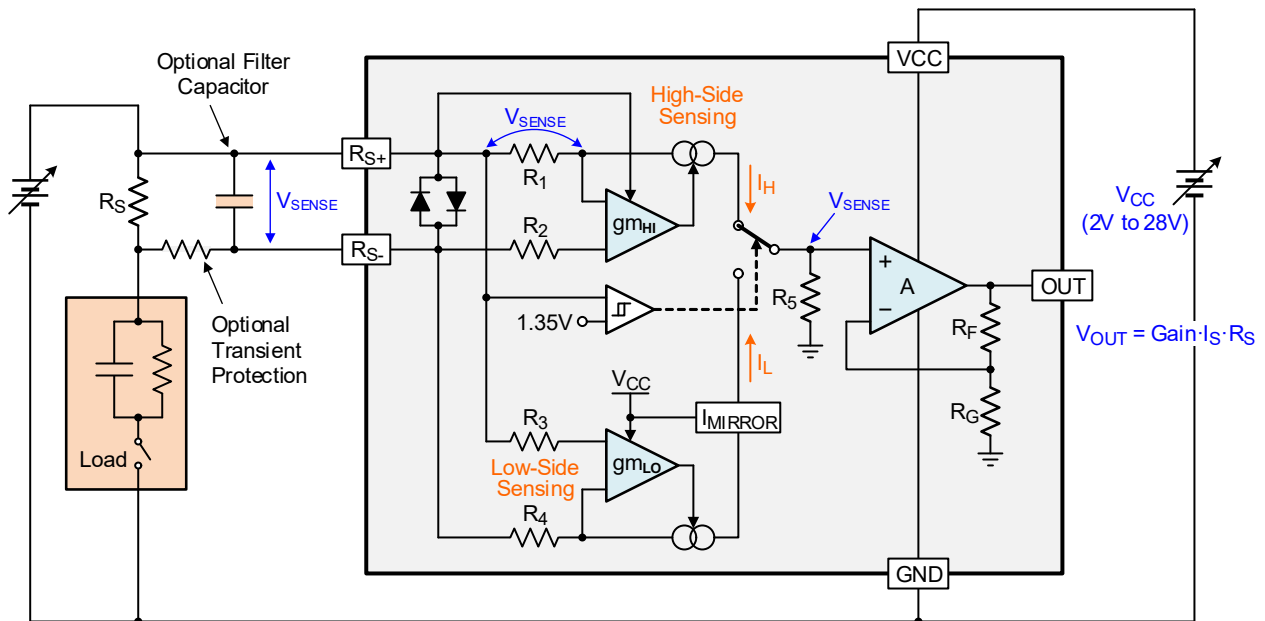

Figure 2. ISL28006 Highly Integrated and Accurate Current Sense Amplifier

A high voltage op amp can be used in a standard differential amp configuration, but this circuit requires extremely tight resistor matching when amplifying low voltages on high voltage rails. For example, if sensing 10mV on a 5V rail using 1% resistors, amplifying by 50 and assuming a zero offset in the amp, the worst-case error is ~37%.

Figure 3 shows this numeric example of the worst-case tolerance. The voltage at the non-inverting terminal of the amplifier is calculated to be 4.9137V based on the worst case values of 0.99kΩ and 50.5kΩ for the resistor divider and the voltage at the inverting terminal is the same by virtual null. The current in the 1.01kΩ resistor is

(5V - 4.9137V)/1.01kΩ = 85.4µA. The output is 4.9137V - 85.4µA × 49.5kΩ = 683mV. This is 37% higher than the nominal value of 50 × 10mV = 500mV that one would expect with 50kΩ and 1kΩ resistors.
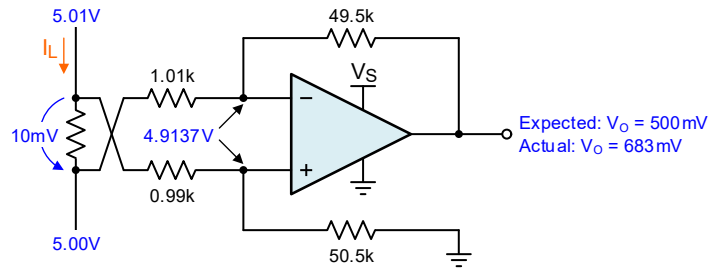

Figure 3. Differential Amplifier Configuration with 1% Tolerance Resistors

One important item of note: The differential amp configuration in Figure 2 requires the use of an amp with a voltage rating on the order of the high rail being sensed. There is much better availability of low offset op amps that operate from a 5V nominal supply rail than amps that operate at higher supply rails. Best in class 5V amps have µVs of offset. Best in class high voltage (30~40V) amps have 10µV to 100µV offset.

2. Improved Current Sense Circuits

The remainder of this application note explores two circuit techniques (Figure 4 and Figure 5), which allow the use of conventional 5V op amps for sensing current on high voltage rails. A simple, low power consumption biasing scheme is used to power the amplifier. In addition, the gain-bandwidth of the overall circuit can be much higher than the gain bandwidth of the amp itself.

This can be a significant advantage in applications where the objective is to sense the current in a switching supply running at hundreds of kHz and be able to retain the high frequency harmonics.

One circuit technique is shown in Figure 4. This example shows the shunt on a 12V rail being measured by the ISL28133 chopper stabilized amplifier. Because of negative feedback, the voltage across the shunt also appears across resistor R_9, determining the current through R_9. This same current flows through the drain and source of buffer transistor Q_3 and through R_7, generating a voltage with respect to ground that is proportional to the high-side current. The total error in amplifying the shunt voltage is the error because of R_7, R_9 and the offset voltage. With 0.1% resistors and the 8µV offset of the ISL28133, the error in sensing 10mV is <0.3%. (0.1% from each resistor, 8µV/10mV = 0.08% error from the offset). This is >10x better accuracy than the differential amp in Figure 3.
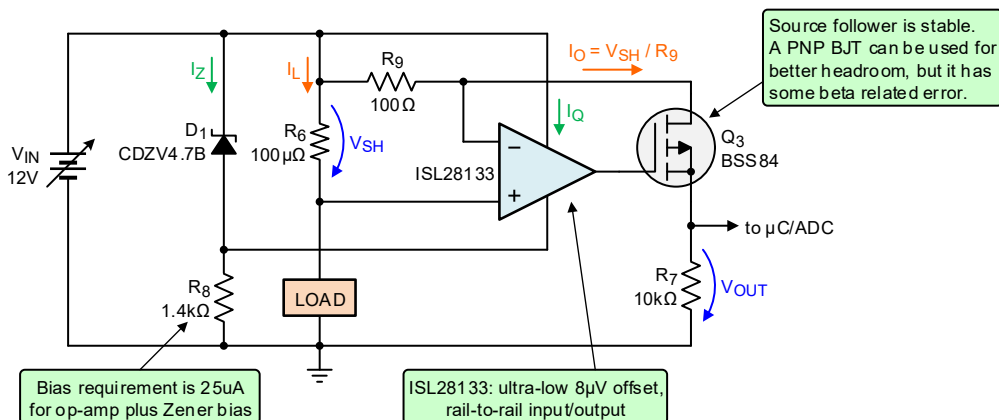

Figure 4. Simple Level Shift Circuit using a Low-Voltage Amplifier

Note: This circuit can be biased without much dissipation using resistor R_8 and Zener diode D_1. Resistor R_8 needs to only provide supply current for the ISL28133 (25µA) and ~5mA to bias the Zener diode.

Even with a 48V high-side rail, the total power to bias the amplifier is only ~48V*1.025µA = 50mW. There will be additional power in Q_3 (this will depend on the level shift current in the drain of Q_3) but this can be as low as 100µA, resulting in a power loss of 5mW.

The circuit in Figure 4 works extremely well, but it has two limitations explained as follows:

▪ If the load shorts, the current sense circuit no longer functions. Current sensing with the load shorted is required in many applications where V_{IN} is the output voltage of a switching supply. Many times, this current sense circuit is used as part of the short circuit protection for the switching supply, so it must be functional during a load short.

▪ It is advantageous in some power applications to use DCR sensing, a well-known technique where a resistor-capacitor combination across an inductor, is used to sense the inductor current. The level shift current would run through this resistor, seriously degrading the accuracy.

Figure 5 shows a modified version of the circuit in Figure 4, which resolves these limitations. This example shows the use of DCR sensing in a switching supply. To use this technique, a 5V bias that rides on top of the output voltage is required. In most switching supplies, this bias is usually easy to obtain from either a higher voltage rail or by peak charging from one of the switching nodes. Other changes from Figure 4 are that the op amp output buffer transistor (Q_1) has been changed to an NPN type and, to level shift to ground, a current mirror consisting of matched pair Q_{3a}-Q_{3b} and R_1/R_2 has been added.
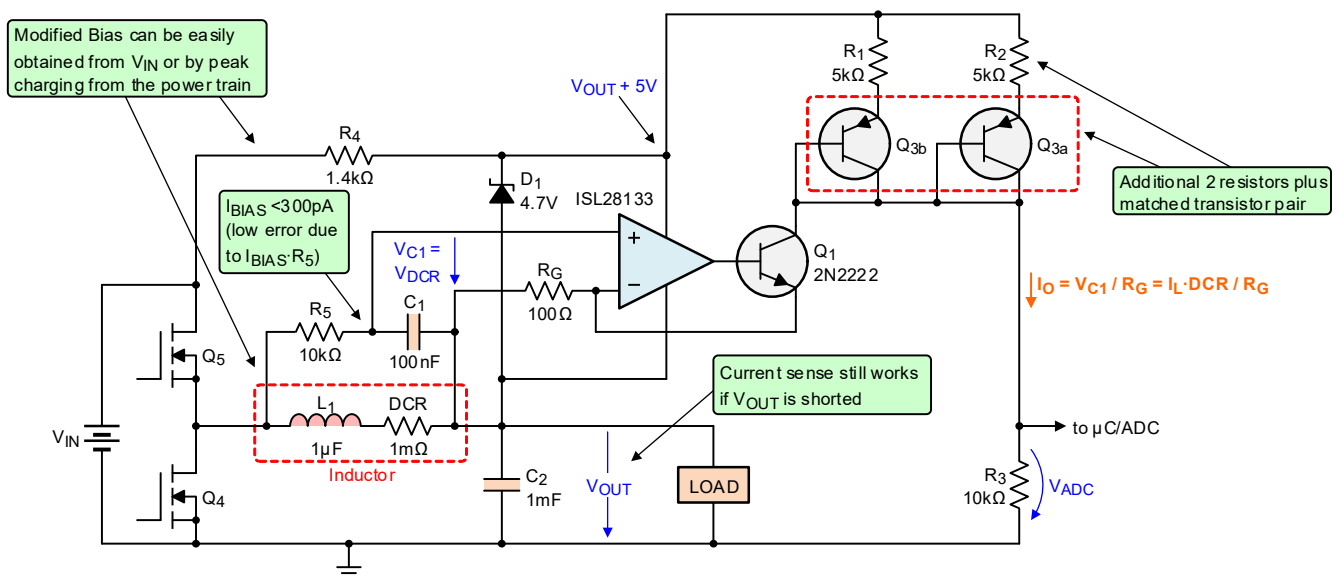

Figure 5. Modified Sense Configuration using DCR Sensing in a Buck Converter

Matched transistor pairs are commercially available in a single package with V_{be} matching of ±1mV. Proper sizing of R_1/R_2 can minimize the error because of V_{be} mismatch. When compared to the circuit in Figure 4, this circuit still has the additional inaccuracy because of resistors R_1, R_2, and the V_{be} mismatch. The overall error is likely to be 2x higher than the circuit of Figure 4 with components of similar tolerance.

Note: This new circuit can also sense a shunt resistor but is shown using DCR sensing. The RC circuit across the inductor is used to sense the current in the inductor and the voltage across C_1 equals the load current times the DCR in steady state. If $R_5 \times C_1 = L_1/DCR$, the circuit not only matches V_{C1} to V_{DCR} in steady state, but also matches it during transients[1]. Because of power dissipation in R_5, its value cannot be arbitrarily lowered.

Some sensing configurations can draw significant current through R_5, resulting in significant error. In this configuration, only the bias current of the amp runs through R_5. In this example, the bias current of the ISL28133 is 300pA. In most cases, this results in negligible error.

Refer to the following notes regarding the circuits in Figure 4 and Figure 5.

- The manner in which the buffer transistor is configured should not destabilize the amp if it is internally compensated to be unity gain stable. The emitter of the buffer transistor follows the output of the amplifier, and this buffering is therefore the equivalent of tying the output back to the inverting input, as in a unity gain configuration.

- The buffer transistor Q_1 does relieve the gain-bandwidth restrictions of the op amp. The configuration in Figure 5 has a gain of $R_3/R_G = 100$ from V_{C1} to the output. Figure 6 shows the simulated frequency response of this circuit using the ISL28133. The gain-bandwidth of the amp is 400kHz, yet the overall circuit gain bandwidth is $100 \times 100kHz = 10MHz$. The buffer transistor improves the bandwidth without destabilizing the op amp.

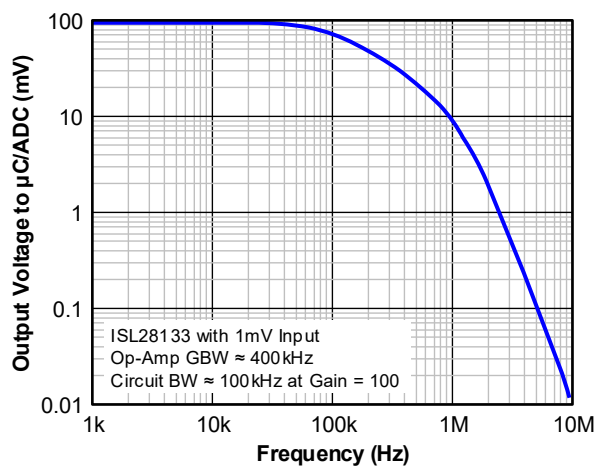**Figure 6. Frequency Response of the Circuit in Figure 5 (The Input is 1mV at the Point Labels Vc1 = V_{DCR} in Figure 5. The Output is at the Point Labeld to μC/ADC)**

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1. Current-Sensing Techniques for DC/DC Converters, Hassan Pooya Forghani-zadeh, Gabriel A. Rincón-Mora, Georgia Tech Analog Consortium, School of Electrical and Computer Engineering, Georgia Institute of Technology

- A higher bandwidth amplifier can be used to accurately replicate the current waveform in a switching power supply. The ISL28134 has a GBW (gain-bandwidth) of 3.5MHz and only 2.5µV offset. The ISL28191 has 61MHz GBW with a max offset of 630µV. Figure 7 shows the simulated response of the circuit in Figure 5, using the ISL28191 when a 10mV square wave is imposed across V_{C1}. The circuit amplifies the signal by 100x and replicates this 500kHz waveform with little loss of the higher frequency harmonics. This can be extremely useful for peak current detection in switching supplies.
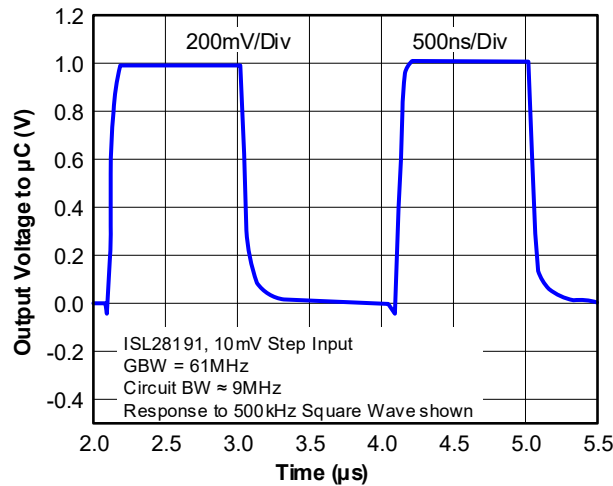
Figure 7. Simulated Response of the Circuit in Figure 5. The ISL28191 is used in Place of the ISL28133

3. Summary

This application note has presented two new circuit techniques for measuring high-side current in a power application. Compared with a standard difference amp configuration, the two configurations offer considerably better accuracy as well as significantly higher gain bandwidth product. The implementation only requires the addition of a few low cost components.

4. Revision History

Revision	Date	Description
1.00	Feb 7, 2022	Applied New Template. Updated all Figures. Tweaked text throughout to accommodate for figure updates. Added Revision History section.
0.00	May 1, 2013	Initial release

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