Application Note 1827

Author: Ray Pilukaitis

High-Side, High Current Sensing Techniques

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.

There are various ways to sense high-side current, but no "one fit all" solution. The ISL28006 (see Figure 2), is a very 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. 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 minus 4.9137V)/1.01kΩ = 85.4µA. The output is 4.9137V minus 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.

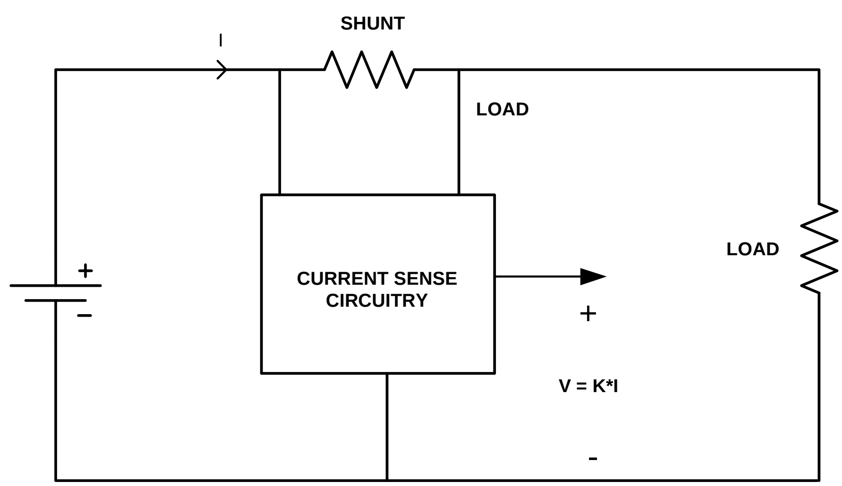

FIGURE 1. SIMPLIFIED BLOCK DIAGRAM

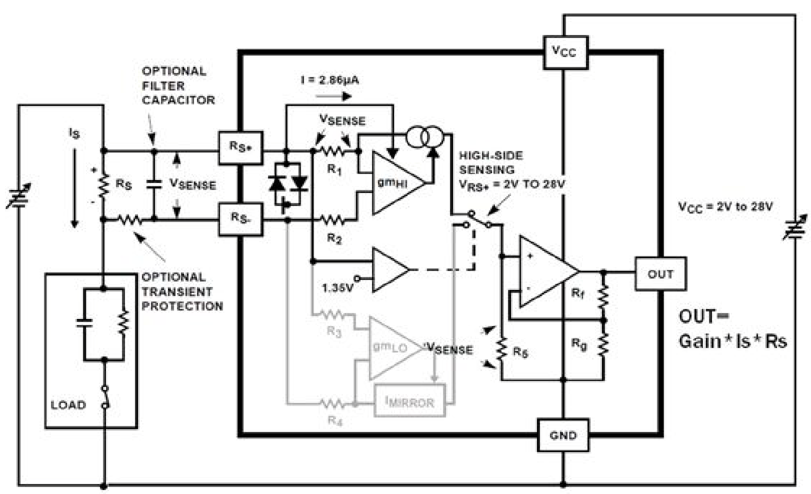

FIGURE 2. ISL28006 HIGHLY INTEGRATED AND ACCURATE CURRENT SENSE AMPLIFIER

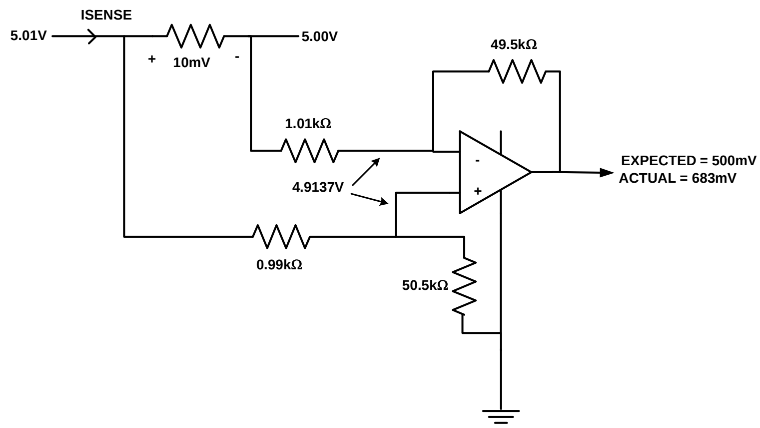

FIGURE 3. DIFFERENCE AMP CONFIGURATION WITH WORST CASED 1% TOLERANCED RESISTORS (1kΩ and 50kΩ)

One important item of note: The differential amp configuration in Figure 2 on page 1 will require 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 which operate from a 5V nominal supply rail than amps which operate at higher supply rails. Best in class 5V amps have µV's of offset. Best in class high voltage (30~40V) amps have 10µV to 100µV offset.

Improved Current Sense Circuits

The remainder of this application note explores two circuit techniques (Figures 4 and 5), which allow 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. By virtual null principles, the voltage across the shunt also appears across resistor R9, determining the current through R9. This same current flows through the drain and source of buffer transistor Q3 and through R7, 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 due to R7, R9 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.

Note that this circuit can be biased without much dissipation using resistor R8 and zener diode D1. Resistor R8 needs to only provide supply current for the ISL28133 (25µA) and ~1mA 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 Q3 (this will depend on the level shift current in the drain of Q3) 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 2 limitations explained as follows:

1. 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.
2. It is advantageous in some power applications to utilize "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 (Q1) has been changed to an NPN type and, in order to level shift to ground, a current mirror consisting of matched pair Q3a-Q3b and R1/R2 has been added. Matched transistor pairs are commercially available in a single package with Vbe matching of ±1mV. Proper sizing of R1/R2 can minimize the error due to Vbe mismatch. When compared to the circuit in Figure 4, this circuit will still have the additional inaccuracy due to resistors R1, R2 and the Vbe mismatch. The overall error is likely to be 2x higher than the circuit of Figure 4 with components of similar tolerance.

Note that 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 C1 will equal the load current times the DCR in steady state. If R5*C1 = L1/DCR, the circuit will not only match Vc1 to Vdcr in steady state, but also match it during transients.[1] Because of power dissipation in R5, its value cannot be arbitrarily lowered. Some sensing configurations can draw significant current through R5, resulting in significant error. In this configuration, only the bias current of the amp runs through R5. In this example, the bias current of the ISL28133 is 300pA. In most cases, this will result in negligible error.

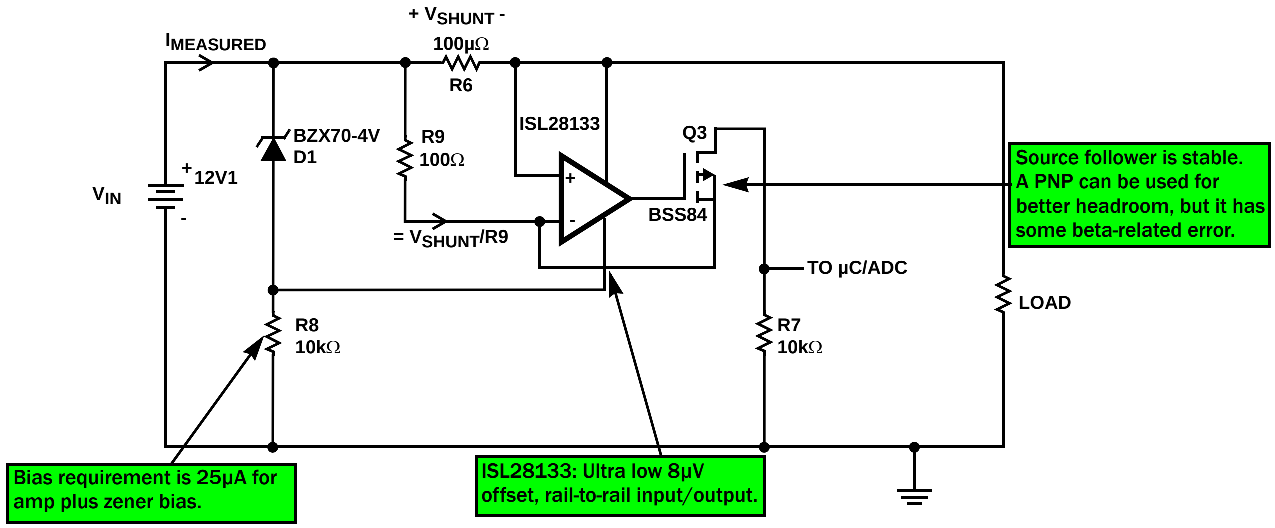

FIGURE 4. SIMPLE LEVEL SHIFT CIRCUIT USING A LOW VOLTAGE AMPLIFIER

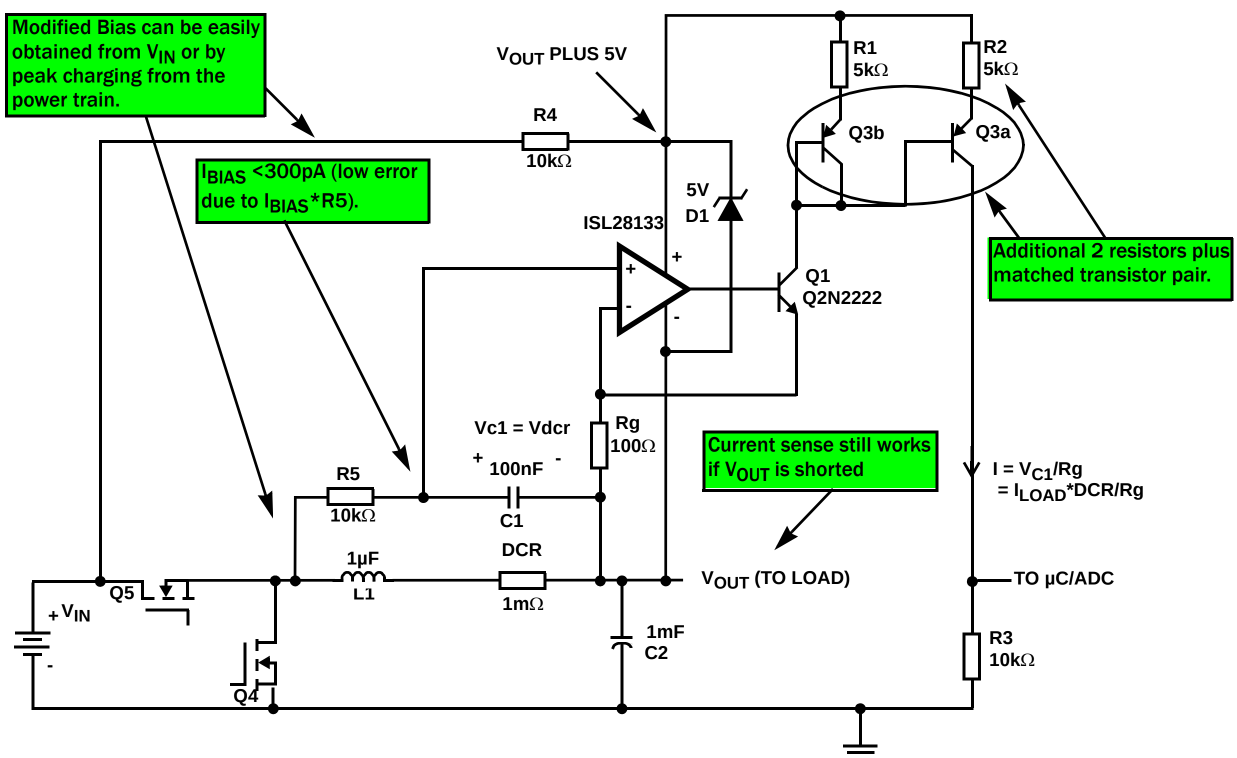

FIGURE 5. MODIFIED SENSE CONFIGURATION USING DCR SENSING IN A BUCK CONVERTER

Here are some additional items of note regarding the circuits in Figures 4 and 5.

1. 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 amp and this buffering is therefore the equivalent of tying the output back to the inverting input, as in a unity gain configuration.
2. The buffer transistor Q1 does relieve the gain-bandwidth restrictions of the op amp. The configuration in Figure 5 has a gain of R3/Rg = 100Ω from Vc1 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*100kHz or 10MHz. The buffer transistor improves the bandwidth without destabilizing the op amp.
3. 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 Vc1. 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.

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.

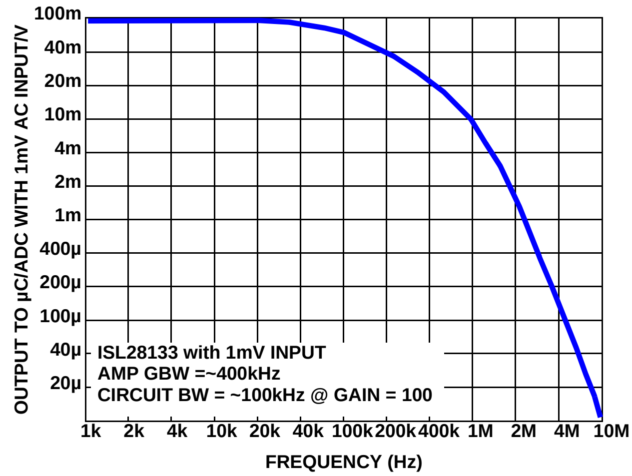

FIGURE 6. FREQUENCY RESPONSE OF THE CIRCUIT IN FIGURE 5 (THE INPUT is 1mV AT THE POINT LABELS “Vc1” IN FIGURE 5. THE OUTPUT IS AT THE POINT LABELS TO “µC/ADC”

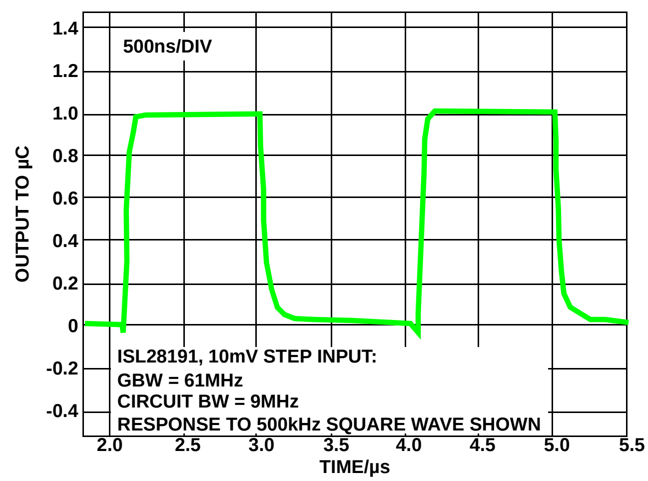

FIGURE 7. SIMULATED RESPONSE OF THE CIRCUIT IN FIGURE 5 TO A $10MV_{P-P}$ SQUARE WAVE AT "Vc1". THE ISL28191 IS USED IN PLACE OF THE ISL28133

References

[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