AN-1318
APPLICATION NOTE

Differential Overvoltage Protection Circuits for Current Sense Amplifiers
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INTRODUCTION

Most current sense amplifiers are capable of handling high common-mode voltages (CMVs) but not high differential input voltages. In certain applications, there are fault conditions wherein the differential input voltage at the shunt exceeds the specified maximum voltage of the amplifier. These conditions can cause damage to the amplifier. This application note introduces two basic overvoltage protection circuits for current sense amplifiers and discusses the effects of the circuits on device performance for two types of current sense architectures—a current sense amplifier (using the AD8210 as an example) and a difference amplifier (using the AD8418 as an example).

OVERVOLTAGE PROTECTION CIRCUIT

Figure 1 shows the basic connection for overvoltage protection of a current sense amplifier. When the differential input voltage exceeds the maximum rated value for a given amplifier, the amplifier may begin to pull current into the internal protection diodes. The additional series resistors, R1 and R2, prevent large current flow to the internal protection diodes if a large differential voltage signal is present between the input pins.
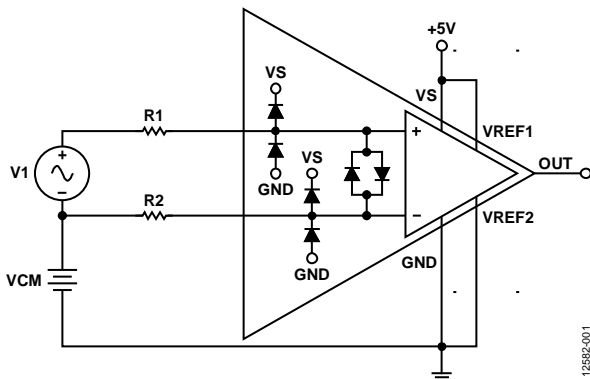

Figure 1. Basic Overvoltage Protection Circuit

Both the maximum rated voltage and the maximum input current tolerated by a protection circuit vary from device to device. As a general rule, limit the current passing through the internal differential protection diodes to 3 mA. Given this value, calculate the values of R1 and R2 using Equation 1.

$$\frac{V_{IN\_MAX} - V_{RATED\_MAX}}{R} = 3 \text{ mA} \tag{1}$$

where:
V_{IN_MAX} is the expected maximum differential voltage.
V_{RATED_MAX} is the maximum rated voltage (0.7 V).
R is the total series resistance (R1 + R2).

For example, if the expected maximum transient input voltage is 10 V, the equation is

$$\frac{10 \text{ V} - 0.7 \text{ V}}{R} = 3 \text{ mA} \tag{2}$$

If R = 3.1 kΩ, then based on Equation 1, R1 and R2 = 1.55 kΩ.

These values for R1 and R2 are significant, relative to the input impedance of certain amplifiers, and can contribute a large error to the overall system performance. Keep the values of R1 and R2 as low as possible to minimize error contribution. One way to reduce the value of R1 and R2 is to add external protection diodes with higher current capabilities on the input pins, as shown in Figure 2.
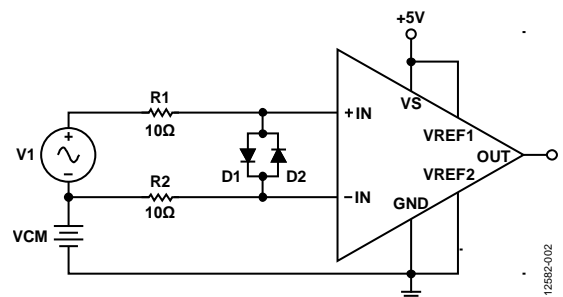

Figure 2. Overvoltage Protection Circuit with External Input Differential Protection Diodes

For example, when using the Digi-Key B0520LW-7-F Schottky diode, which can handle up to 500 mA of forward current, the value of R decreases to 20 Ω.

In addition to protection against overvoltage, R1 and R2 can also be used to form an electromagnetic interference (EMI) filter by adding capacitors, as shown in Figure 3. This configuration helps the circuit reject any high frequency interference from external sources such as mobile communications, electric motors, and utility power lines.
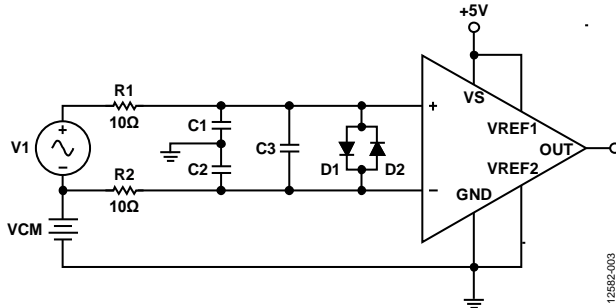

Figure 3. Overvoltage Protection Circuit with EMI Filters

There are two types of bandwidths to consider for this type of EMI filter circuit—differential and common-mode. These bandwidths are determined using Equation 3 and Equation 4, respectively.

Differential Filter Bandwidth $(-3\text{ dB}) =$

$$\frac{1}{2\pi \times (R1 + R2) \times \left(\dfrac{C1 \times C2}{C1 + C2} + C3\right)} \quad (3)$$

Common-Mode Filter Bandwidth $(-3\text{ dB}) =$

$$\frac{1}{2\pi \times R1 \times C1} \quad (4)$$

TRADE-OFFS IN SYSTEM PERFORMANCE

Adding series resistors to the input of the amplifier can degrade certain performance parameters. In some amplifiers, R1 and R2 appear in series with internal precision resistors. In other amplifiers, offset currents work with the resistors to create offset voltages. The parameters most likely to be affected are gain error, common-mode rejection ratio (CMRR), and offset voltage.

The test setup used for evaluating gain error, CMRR, and offset voltage is shown in Figure 4. This setup uses the Agilent E3631A power supply for providing the 5 V single-supply to the device, the Yokogawa GS200 precision dc source for the differential input voltage signal, the HAMEG HMP4030 for setting the CMV, and the Agilent 3458A precision multimeter for measuring the output voltage of the current sense amplifiers.
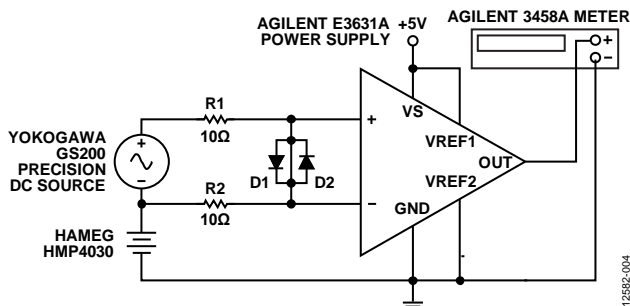

Figure 4. Test Setup for Evaluating the Gain Error, CMRR, and Offset Voltage

Both the AD8210 and the AD8418 are evaluated to measure the impact of the additional series resistors on the gain error, CMRR, and offset voltage parameters of the devices.

Gain Error

The gain error of an amplifier is usually specified in the corresponding data sheet. Table 1 shows the calculated additional gain error and the actual gain error of the AD8210.

The AD8418 is tested with and without the protection circuit. Table 2 shows the calculated additional gain error and the actual gain error of the amplifier.

Common-Mode Rejection Ratio

Because current sense amplifiers are usually exposed to environments with high CMV, CMRR is one of the most important specifications. CMRR assesses the ability of a device to reject high CMVs and attain optimal accuracy and performance. It refers to a measure of change in output voltage when equal voltage is applied at the two input terminals of the amplifier. CMRR is defined as a ratio of the differential gain to the common-mode gain and is usually specified in decibels.

Use Equation 5 and Equation 6 to find the CMRR values for both amplifiers.

$$CMRR = \left|\frac{A_{DM}}{A_{CM}}\right| = \left|\frac{20 \times \Delta V_{CM}}{\Delta V_{OUT}}\right| \quad (5)$$

$$CMRR = 20 \log \left(\left|\frac{20\Delta V_{CM}}{\Delta V_{OUT}}\right|\right) \quad (6)$$

where:
A_{DM} is the differential gain of the AD8210 and the AD8418 ($A_{DM} = 20$).
A_{CM} is the common-mode gain, $\Delta V_{OUT}/\Delta V_{CM}$.

The CMRR measurement results for the AD8210 and the AD8418 current sense amplifiers are shown in Table 3 and Table 4, respectively.

The results indicate that the effect of the additional external series resistors on CMRR performance impacts the AD8418 but does not significantly affect the AD8210.

Table 1. AD8210 Gain Error

R1 (Ω)	R2 (Ω)	Additional Gain Error (%)	Actual Gain (V/V)	Actual Gain Error (%)
0	0	0	19.9781	−0.1095
10.2	10.2	0.497	19.88059	−0.59705

Table 2. AD8418 Gain Error

R1 (Ω)	R2 (Ω)	Additional Gain Error (%)	Actual Gain (V/V)	Actual Gain Error (%)
0	0	0	19.99815	−0.00925
10.2	10.2	0.013	19.9955	−0.0225

Table 3. AD8210 CMRR Performance at a Gain of 20

R1 (Ω)	R2 (Ω)	CMV = 0 V and 4 V (dB)	CMV = 4 V and 6 V (dB)	CMV = 4 V and 65 V (dB)	CMV = 6 V and 65 V (dB)
0	0	−92.77	−104.96	−121.49	−123.35
10.2	10.2	−94.37	−107.99	−121.86	−123.10

Table 4. AD8418 CMRR Performance at a Gain of 20

R1 (Ω)	R2 (Ω)	CMV = 0 V and 35 V (dB)	CMV = 35 V and 70 V (dB)	CMV = 0 V and 70 V (dB)
0	0	−127.72	−123.72	−138.39
10.2	10.2	−88.89	−104.35	−93.05

Table 5. AD8210 Additional Offset Voltage Due to Input Offset Current and External Impedances

R1 (Ω)	R2 (Ω)	V$_{OUT}$ (mV)	Additional Offset Voltage (RTI) (µV)
0	0	5.598	17
10.2	10.2	5.938	17

Table 6. AD8418 Additional Offset Voltage Due to Input Offset Current and External Impedances

R1 (Ω)	R2 (Ω)	V$_{OUT}$ (mV)	Additional Offset Voltage (RTI) (mV)
0	0	−0.91	1.3
10.2	10.2	26.09	1.3

Offset Voltage

When bias currents pass through the external resistors, they produce a voltage in series with the intrinsic offset voltage of the device. To compute this additional offset voltage, multiply the input offset current (I_{OS}), the difference between the two input bias currents, by the external impedance present on the input pins, as shown in Equation 7.

$$Offset\ Voltage = I_{OS} \times R \qquad (7)$$

where:
I_{OS} is the input offset current.
R is the additional external impedance.

The increase in offset voltage based on the actual measurements from both the AD8210 and the AD8418 current sense amplifiers are shown in Table 5 and Table 6, respectively.

The results show that the increase in offset voltage in the AD8418 is larger than the increase in offset voltage in the AD8210. This is caused by the considerably high input offset current of the AD8418, which is around 100 µA. Any additional impedances present on the input pins, together with the input offset current, reflect as added offset voltage. Therefore, it is recommended to use smaller values for the series resistors of the AD8418 to minimize the effect on offset voltage.

CONCLUSION

Implementing additional series resistors on the input pins is the simplest way to protect a current sense amplifier against overvoltage. The circuit gives the user extra headroom for the allowable input voltage but at the cost of extra components. The amount of impact on performance such as gain error, CMRR, and offset voltage is measurable and largely related to the magnitude of the total external resistors and the type of current sense amplifier used.

For more information on overvoltage protection for robust amplifiers, see the *Analog Dialogue* article "*Robust Amplifiers Provide Integrated Overvoltage Protection*."

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