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APPLICATION NOTE 3888

Performance of Current-Sense Amplifiers with Input Series Resistors

By: Prashanth Holenarsipur, Manager, Corporate Applications, Amplifiers & Sensors

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Abstract: This application note explains some performance characteristics of high-side current-sense amplifiers. The article explains how to use these amplifiers with series resistors on the sense inputs. This design approach is especially useful for applications that need to amplify small voltages across a sense resistor on a high-voltage rail, and feed it to a low-voltage ADC or a low-voltage analog control loop. Test data from the MAX4173 and the MAX4372 are presented.

Introduction

When discussing functional operation, a current-sense amplifier can be considered an instrumentation/differential amplifier with a floating input stage. This means that even when the device is powered from a single-supply with V_{CC} = 3.3V or 5V, it can amplify input differential signals at a common-mode voltage well beyond these power supply rails. The common-mode voltages in a current-sense amplifier can, for example, be up to 28V (MAX4372 and MAX4173) and 76V (MAX4080 and MAX4081).

This performance characteristic of current-sense amplifiers is extremely useful for high-side current-sensing applications that need to amplify small voltages across a sense resistor on a high-voltage rail, and feed it to a low-voltage ADC or a low-voltage analog control loop. In these applications the current-sense signal frequently needs to be filtered at the source, i.e., across the sense resistor. The design could use either a differential filter (**Figure 1**) to smooth "spiky" load currents and sense voltages, or a common-mode filter (**Figure 2**) to enhance ESD operation/immunity to common-mode voltage spikes and temporary overvoltages. These filters can be successfully implemented by choosing the right component values. If the wrong component values are selected, however, unplanned input offset voltages and gain errors can be introduced, which compromise circuit performance.

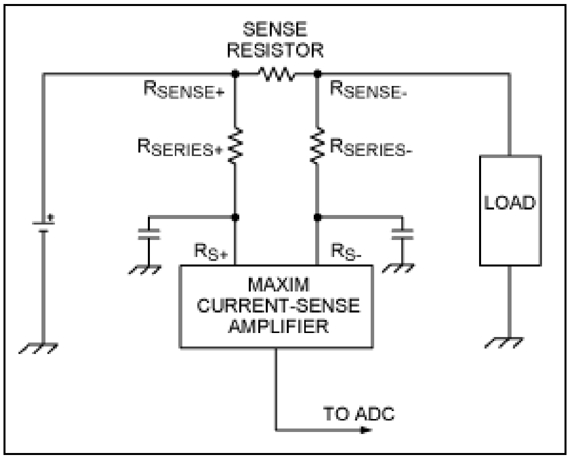

Figure 1. Circuit diagram for a differential filter to smooth spiky load currents.

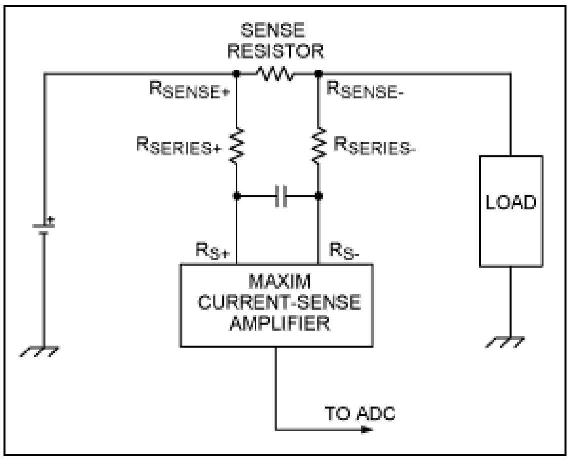

Figure 2. Circuit diagram for a common-mode filter to improve immunity to ESD spikes and common-mode overvoltages.

Determining which Filters to Use

Consider now the MAX4173 current-sense amplifier shown in **Figure 3**. This device has its sense resistor connected directly to the R_{S+} and R_{S-} terminals of the chip. The differential voltage across the sense resistor is reproduced across R_{G1} by internal operational-amplifier function so that $I_{LOAD} \times R_{SENSE} = V_{SENSE} = I_{RG1} \times R_{G1}$. This current ($I_{RG1}$) is then level-shifted and amplified by an internal current mirror to generate the output current, I_{RGD}. The internal circuit for the MAX4173 implements R_{GD} = 12k and R_{G1} = 6k.

Therefore,

$V_{OUT} = R_{GD} \times I_{RGD} = R_{GD} \times Gain \times I_{RG1} = R_{GD} \times Gain \times V_{SENSE}/R_{G1}$

As R_{GD} and R_{G1} are on-chip resistors, their actual values normally vary by as much as ±30% due to semiconductor process variations. However, because it is the ratio of R_{GD} and R_{G1} that determines the final gain accuracy, the final gain is well controlled and can be easily trimmed during manufacture.

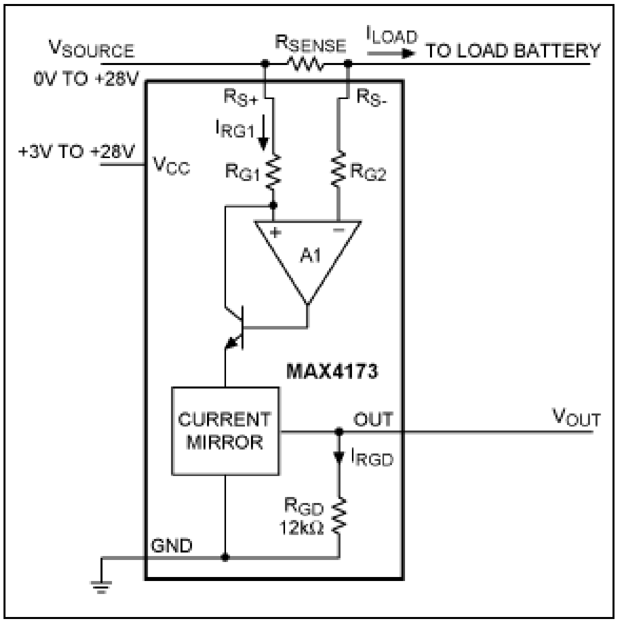

Figure 3. Internal functional diagram of the MAX4173.

However, when series resistors are inserted between the R_{SENSE+} and R_{SENSE-} terminals of a sense resistor, and R_{S+} and R_{S-} pins of the part to implement differential/common-mode filters (as shown in Figure 1 and Figure 2), the chip behaves as though R_{G1} and R_{G2} have been modified. From the above equation, it is apparent that modifying a trimmed R_{G1} introduces a gain error. Further, since the absolute value of R_{G1} can vary by as much as ±30%, this gain error can also vary by ±30% and cannot be controlled or predicted between multiple parts. The only way to control this gain error is, therefore, to ensure that the input series resistor, $R_{SERIES+}$, is small compared to R_{G1}.

Additionally, a mismatch between resistors R_{G1} and R_{G2} is "converted" by the device's input bias currents into an input offset voltage. The MAX4173 and MAX4372 data sheets show that bias current I_{RS-} is twice I_{RS+}, and therefore, any resistor in series with R_{G1} ($R_{SERIES+}$) should be twice that in series with R_{G2} ($R_{SERIES-}$) to cancel the input offset voltage. Similar bias current characteristics are also present for the following current-sense amplifiers: MAX4073, MAX4172, MAX4373–MAX4375 and MAX4376–MAX4378. Therefore, similar techniques can be used to size input resistors for proper differential/common-mode filter design.

Summary and Proof

To summarize, ideal performance can be obtained from input filters with series resistors between the sense resistor and R_{S+} and R_{S-} pins if:

1. The series resistor between R_{SENSE+} and R_{S+} is kept small with respect to R_{G1}.
2. The series resistor between R_{SENSE+} and R_{S+} is twice as big as that between R_{SENSE-} and R_{S-}.

Note, finally, that since $R_{SERIES+}$ is twice $R_{SERIES-}$, the common-mode filter capacitors will also need to be suitably scaled to meet desired AC and transient performance objectives.

The bench-test results in **Table 1** were obtained with MAX4173T and support the discussion above. The min and max values of V_{OS} were calculated using min and max bias currents from the data sheet; the min and max gain errors were calculated using ±30% of R_{G1} = 6k.

Table 1. Series Resistor Test Results for the MAX4173

$R_{SERIES+}$	$R_{SERIES-}$	Ratio of $R_{SERIES+}$ to $R_{SERIES-}$	Gain	$V_{INTERCEPT}$ (mV)	Gain Error	V_{OS} (mV)	V_{OS} (mV, min)	V_{OS} (mV, max)	GE (%, min)	GE (%, max)
0	0	NA	19.959	-1.5974	0.2%	-0.1	0	0.0	0.0%	0.0%
98	98	~1	19.623	53.882	1.9%	2.7	0	4.9	1.2%	2.3%
196	98	~2	19.291	-2.6704	3.5%	-0.1	0	0.0	2.5%	4.5%
994	1000	~1	16.979	491.88	15.1%	29.0	0	50.3	11.3%	19.1%
1977	1000	~2	14.815	-0.9963	25.9%	-0.1	0	1.2	20.2%	32.0%

Similarly, bench results obtained with MAX4372F are shown below in **Table 2** (R_{G1} = 100k).

Table 2. Series Resistor Test Results for the MAX4372

$R_{SERIES+}$	$R_{SERIES-}$	Ratio of $R_{SERIES+}$ to $R_{SERIES-}$	Gain	$V_{INTERCEPT}$ (mV)	Gain Error	V_{OS} (mV)	V_{OS} (mV, min)	V_{OS} (mV, max)	GE (%, min)	GE (%, max)
0	0	NA	49.968	14.253	-0.1%	-0.3	0	0.0	0.0%	0.0%
1000	997	~1	49.442	40.34	-1.1%	-0.8	0	-1.0	-0.8%	-1.4%
2098	1048	~2	48.877	13.7	-2.2%	-0.3	0	0.0	-1.6%	-2.9%
10001	9978	~1	45.197	245.69	-9.6%	-5.4	0	-10.0	-7.1%	-12.5%
19958	9978	~2	41.278	8.4646	-17.4%	-0.2	0	0.0	-13.3%	-22.2%

The derivation of calculated min and max gain errors and min-max V_{OS} is shown below.

Old Gain

$= \text{Constant} \times R_{GD}/R_{G1} = 20$ (for T-version of MAX4173)

New Gain

$= \text{Constant} \times R_{GD}/R_{G1new}$; $R_{G1new} = R_{G1} + R_{SERIES+}$
$= \text{Old Gain} \times R_{G1}/R_{G1new}$
$= 20 \times R_{G1}/(R_{G1} + R_{SERIES+})$

Gain Error

$= (20 - \text{New Gain})/20\%$
$= R_{SERIES+}/(R_{G1} + R_{SERIES+})$

Min Gain Error

$= R_{SERIES+}/(1.3 \times R_{G1} + R_{SERIES+})$

Max Gain Error

$= R_{SERIES+}/(0.7 \times R_{G1} + R_{SERIES+})$

R_{G1} = 6k for MAX4173

$V_{OS} = I_{BIAS2} \times R_{G2new} - I_{BIAS1} \times R_{G1new}$
$= I_{BIAS1} \times ((2 \times R_{SERIES-}) - R_{SERIES+})$; where $I_{BIAS2} = 2 \times I_{BIAS1}$

$I_{BIAS1}(min) = 0$
$I_{BIAS1}(max) = 50\mu A$ for MAX4173

A similar article first appeared on the *Planet Analog* website on September 26, 2007.

Related Parts		
MAX4073	Low-Cost, SC70, Voltage-Output, High-Side Current-Sense Amplifier	Free Samples
MAX4172	Low-Cost, Precision, High-Side Current-Sense Amplifier	Free Samples
MAX4173	Low-Cost, SOT23, Voltage-Output, High-Side Current-Sense Amplifier	Free Samples
MAX4372	Low-Cost, UCSP/SOT23, Micropower, High-Side Current-Sense Amplifier with Voltage Output	Free Samples
MAX4373	Low-Cost, Micropower, High-Side Current-Sense Amplifier + Comparator + Reference ICs	Free Samples
MAX4374	Low-Cost, Micropower, High-Side Current-Sense Amplifier + Comparator + Reference ICs	Free Samples
MAX4375	Low-Cost, Micropower, High-Side Current-Sense Amplifier + Comparator + Reference ICs	Free Samples
MAX4376	Single/Dual/Quad High-Side Current-Sense Amplifiers with Internal Gain	Free Samples
MAX4377	Single/Dual/Quad High-Side Current-Sense Amplifiers with Internal Gain	Free Samples
MAX4378	Single/Dual/Quad High-Side Current-Sense Amplifiers with Internal Gain	Free Samples

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