AN3222
Application note

Demonstration board user guidelines for low-side current sensing with the TS507 operational amplifier

Introduction

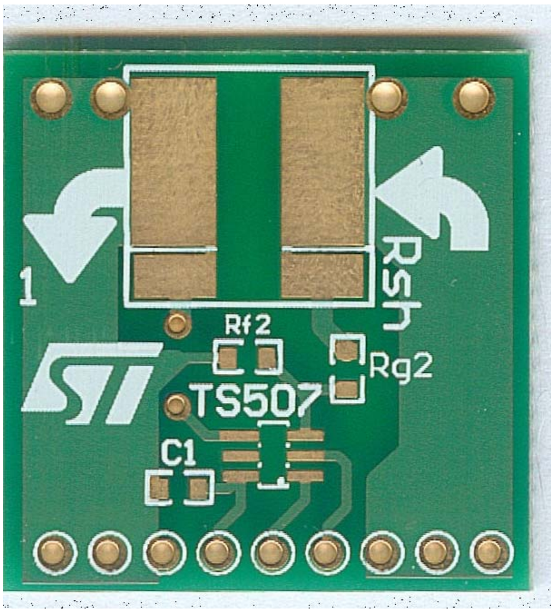
This application note describes the STEVAL-ISQ013V1, a demonstration board specifically designed for low-side current sensing with the TS507 operational amplifier.

Power management mechanisms are found in most electronic systems. Current sensing is useful for protecting your applications. The low-side current sensing method consists in placing a sense resistor between the load and the circuit's ground. The resulting voltage drop is amplified using the TS507.

This document describes how to accurately measure the current in your applications. It provides:

- the advantages of the low-side current sense method.
- the schematics and layout of the demonstration board.
- a description of the TS507's main features.
- a method for selecting the most appropriate components for your application.
- theoretical and practical results.

Figure 1. Demonstration board



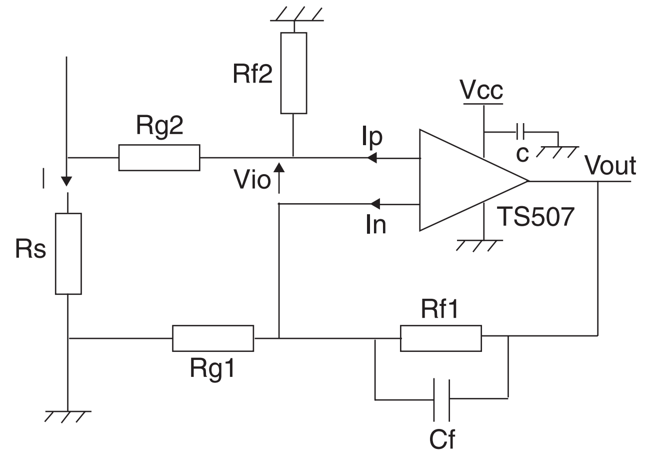
1 Advantages of the low-side current sense method

The common-mode voltage is close to ground, despite the voltage of the power source. Therefore, the current sense voltage can be amplified by a low-voltage operational amplifier (no Vicm restriction).

2 Schematic and layout of the demonstration board

Figure 2 represents the board’s schematics.

Figure 2. Demonstration board schematics



The demonstration board has the following features.

- Board dimensions: 27 x 24 mm
- 2-layer PCB
- PCB thickness: 0.8 mm
- FR4 material
- Copper thickness: 18 µm

Figure 3. Demonstration board: top view

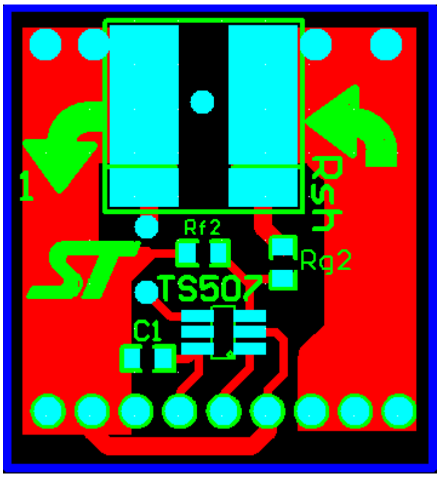
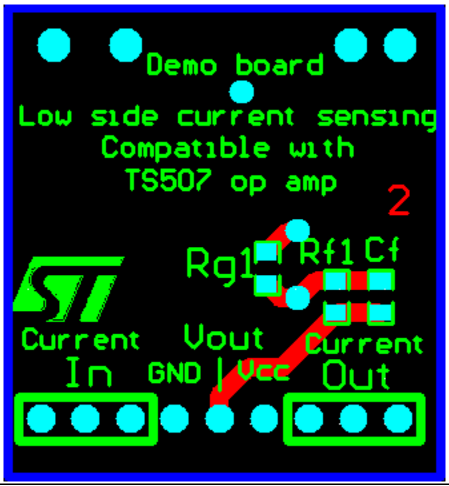


Figure 4. Demonstration board: bottom view



3 TS507 features

The TS507 operates from 2.7 to 5.5 V. The device has a rail-to-rail configuration on both its input and output. At 25°C it demonstrates the following features.

- Vio = 25 µV typ, 100 µV max
- AVD = 131 dB (typical Vcc = 5 V)
- GBP = 1.9 MHz
- Vol = 4 mV typ, 15 mV max, with R_L = 10 kΩ

Additional information on the TS507 can be found at:
http://www.st.com/stonline/products/families/amplifiers_comparators/opamps/ts507amp.htm

4 Selecting the components

Depending on the type of application, various component values can be selected, such as *Rshunt* or resistors for the amplifier gain.

To select the correct component values:

1. **Find the maximum current.**
   This is the maximum current that goes through the sensing resistor (the maximum current to sense in your system).

   For example:

   $$\mathrm{Imax} = \mathrm{Power\_max} / \mathrm{voltage} = 5\ \mathrm{W} / 5\ \mathrm{V} = 1\ \mathrm{A}$$

2. **Find the correct shunt resistor.** This value must be limited to avoid a significant voltage drop (such as 1%) and to limit power dissipation. It must, however, be high enough to obtain better accuracy.

   For example: Vsense_max = 1% voltage, with voltage = 5 V and Imax = 1 A

   $Rshunt \times Imax \le Vsense\_max$

   $$\Rightarrow \mathrm{Rshunt} \le \frac{1\% \cdot 5\ \mathrm{V}}{1\ \mathrm{A}}$$

   So Rshunt must be lower than or equal to 50 mΩ. In the current example, Rshunt has been set to 30 mΩ

3. **Calculate the maximum power dissipation in the shunt resistor.** To avoid damaging the sensing resistor, the shunt resistor has to sustain a suitable wattage.

   For example:

   $$\mathrm{Pmax} = \mathrm{Rshunt} \cdot \mathrm{Imax}^2 = 0.03 \cdot 1^2 = 0.03\ \mathrm{W}$$

   In this case, a 1 W shunt resistor is sufficient.

4. **Choose the appropriate configuration gain.**

   $$\mathrm{Vout} = (\mathrm{Rf} / \mathrm{Rg}) \cdot \mathrm{V} = (\mathrm{Rf} / \mathrm{Rg}) \cdot \mathrm{Rshunt} \cdot \mathrm{I}$$

   To avoid saturation:

   $$\mathrm{Vout} \le \mathrm{Voh} \Rightarrow \mathrm{Rf} < \frac{\mathrm{Voh} \cdot \mathrm{Rg}}{\mathrm{Rshunt} \cdot \mathrm{Imax}}$$

   In the current configuration, Rg = 100 Ω and Voh = 4.985 V (TS507 at 25°C, Vcc = 5 V).

   $$\mathrm{Rf\ max} = \frac{4.985 \cdot 100}{0.03 \cdot 1} = 16.6\mathrm{k}\Omega$$

   Rf must therefore be lower than 16.6 kΩ to avoid saturation of the TS507 at maximum currents. It is recommended to choose the highest possible Rf to benefit from the output voltage capability of the amplifier. Selecting Rf in the E192 series leads to Rf = 16.2 kΩ

To minimize the offset caused by the input currents, the feedback resistors must be minimized; the higher Rf, the higher the error on *Iio* (see *Equation 2 on page 7*). As such, an Rg of 100 Ω must be considered (the lower Rg, the lower Rf).

Note that if the accuracy obtained is not sufficient, you can go back to step *2.* and increase the Rshunt value.

5 Theoretical and practical measurements

5.1 Theoretical results

Cf helps to stabilize the operational amplifier and can be ignored for the DC analysis.

Using *Figure 2* as reference for the components:

Equation 1

$$\mathrm{Vout} = \mathrm{Rs}\cdot \mathrm{I}\left(1-\frac{\mathrm{Rg2}}{\mathrm{Rg2}+\mathrm{Rf2}}\right)\cdot\left(1+\frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right)+\mathrm{Ip}\left(\frac{\mathrm{Rg2}\cdot\mathrm{Rf2}}{\mathrm{Rg2}+\mathrm{Rf2}}\right)\cdot\left(1+\frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right)-\mathrm{In}\cdot\mathrm{Rf1}-\mathrm{Vio}\left(1+\frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right)$$

Equation 2

$$\mathrm{Vout} = \mathrm{Rs}\cdot \mathrm{I}\frac{\mathrm{Rf}}{\mathrm{Rg}}-\mathrm{Vio}\cdot\left(1+\frac{\mathrm{Rf}}{\mathrm{Rg}}\right)+\mathrm{Rf}\cdot\mathrm{Iio}$$

This equation can be simplified assuming Rf2 = Rf1 = Rf, and Rg2 = Rg1 = Rg.

Only errors due to Vio and Iio remain.

If we also consider the errors due to inaccuracies of the resistors, we obtain with a first-order limited development and with:

$$\mathrm{Vth} = \mathrm{Rs}\cdot\mathrm{I}\cdot\frac{\mathrm{Rf}}{\mathrm{Rg}}$$

Equation 3

$$\mathrm{Vout} = \mathrm{Vth}\left(1+\frac{\Delta\mathrm{Rs}}{\mathrm{Rs}}+\frac{\mathrm{Rf}}{\mathrm{Rf}+\mathrm{Rg}}\left(\frac{\Delta\mathrm{Rf1}}{\mathrm{Rf1}}-\frac{\Delta\mathrm{Rg1}}{\mathrm{Rg1}}\right)+\frac{\mathrm{Rg}}{\mathrm{Rf}+\mathrm{Rg}}\left(\frac{\Delta\mathrm{Rf2}}{\mathrm{Rf2}}-\frac{\Delta\mathrm{Rg2}}{\mathrm{Rg2}}\right)\right)+\mathrm{Rf}\cdot\mathrm{Iio}-\mathrm{Vio}\left(1+\frac{\mathrm{Rf}}{\mathrm{Rg}}\right)$$

As you can see, with correct resistor matching (Rf and Rg) on the inputs, *Iib* does not have any influence on Vout.

$\frac{\Delta R}{R}$ is the resistance tolerance.

For example: 0.1% in our case for Rg and Rf, and 1% for Rshunt.

If the accuracy of the resistors Rf1, Rf2, Rg1 and Rg2 = ε_1 and the accuracy of Rshunt = ε_2, these inaccuracies create a maximum deviation of $(2.\varepsilon_1 + \varepsilon_2)$Vth as shown in *Equation 4*.

Equation 4

$$\mathrm{Vth}\left(\frac{\Delta\mathrm{Rs}}{\mathrm{Rs}}+\frac{\mathrm{Rf}}{\mathrm{Rf}+\mathrm{Rg}}\left(\frac{\Delta\mathrm{Rf1}}{\mathrm{Rf1}}+\frac{\Delta\mathrm{Rg1}}{\mathrm{Rg1}}\right)+\frac{\mathrm{Rg}}{\mathrm{Rf}+\mathrm{Rg}}\left(\frac{\Delta\mathrm{Rf2}}{\mathrm{Rf2}}+\frac{\Delta\mathrm{Rg2}}{\mathrm{Rg2}}\right)\right)=\mathrm{Vth}\left(\varepsilon 2+\frac{\mathrm{Rf}}{\mathrm{Rf}+\mathrm{Rg}}2\cdot\varepsilon 1+\frac{\mathrm{Rg}}{\mathrm{Rf}+\mathrm{Rg}}2\cdot\varepsilon 1\right)$$

$$=\mathrm{Vth}(\varepsilon 2+2\cdot\varepsilon 1)$$

Equation 3 can be simplified to become:

Equation 5

$$\mathrm{Vout} = \mathrm{Vth}+\varepsilon\%\cdot\mathrm{Vth}+\mathrm{Rf}\cdot\mathrm{Iio}-\mathrm{Vio}\left(1+\frac{\mathrm{Rf}}{\mathrm{Rg}}\right)$$

Figure 5 on page 8 depicts the theoretical behavior of the above-defined application.

Vout_th, *Vout_min* and *Vout_max* are represented from the left Y-axis.

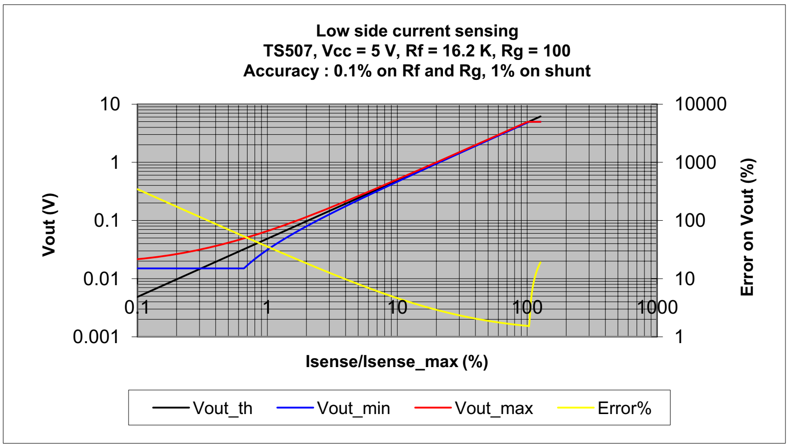
Vout_min and *Vout_max* take into consideration Voh, Vol and errors caused by inaccuracies of the input currents, Vio or the resistors. The measured values should therefore be between these curves.

The error on output (in yellow) is represented from the right Y-axis and is defined as follows.

Equation 6

$$\text{Error}(\%) = \frac{\text{Max}(|\text{Vout\_max} - \text{Vout\_th}|, |\text{Vout\_min} - \text{Vout\_th}|)}{\text{Vout\_th}} \cdot 100$$

Figure 5. Theoretical output voltage and error vs. Is/Imax



Example: if Imax = 1 A, with the same conditions on the resistors as in *Figure 5*:

- Isense = 0.1A, Isense/Imax = 10%
  => the error on the measured voltage is lower than 5% at 10% full scale of Isense.
- Isense = 0.5A, Isense/Imax = 50%
  => the error on the measured voltage is lower than 2% at 50% of the full-scale Isense.

Note that when Isense is used to its full scale, the offset caused by Vio and the input bias current is limited and the errors on the output voltage converge towards the predicted value of 2 × 0.1% + 1% = 1.2%

The accuracy of the measured value depends on the accuracy of the resistors Rf, Rg and Rshunt but also on Vsense_max and of course the amplifier. *Table 1* shows the maximum error for various configurations of the TS507 while applying the method described in this application note.

Table 1. Maximum error on measured value depending on Imax for TS507

Imax	Rs (Ω)	Rg (Ω)	Rf (Ω)	Isense/Imax (%)				
	ε = 1%	ε = 0.1%	ε = 0.1%	1	3	10	30	100
1	0.05	100	9k76	21	7.6	3.1	1.7	1.4
2	0.02	100	12k1	25.5	9.3	3.6	2	1.4
3	0.01	100	16k2	32	12	4.3	2.3	1.5
4	0.01	100	12k1	25.2	9.2	3.5	2	1.5
5	0.01	100	9k76	22	8.1	3.3	1.9	1.4
7	0.005	100	14k	30.7	11	4.1	2.2	1.5
10	0.005	100	9k76	21.9	8.1	3.3	1.9	1.4
12	0.003	100	13k5	30	10.8	4.1	2.2	1.5
15	0.003	100	10k9	24.2	8.9	3.5	2	1.4
20	0.002	100	12k1	27	9.7	3.8	2.1	1.5
				Max | Error| (%)				

Rs has been calculated for a maximum sense voltage of 50 mV (it represents 1% of the voltage drop for a 5 V voltage source).

5.2 Practical results

This section summarizes the results of four practical measurements (*Figure 6* to *Figure 9*).

- Case 1: Rshunt = 3 mΩ, Rg = 100 Ω, Rf = 150 kΩ, max = 1 A
- Case 2: Rshunt = 10 mΩ, Rg = 100 Ω, Rf = 47,5 kΩ, max = 1 A
- Case 3: Rshunt = 30 mΩ, Rg = 100 Ω, Rf = 16,2 kΩ, max = 1 A
- Case 4: Rshunt = 100 mΩ, Rg = 100 Ω, Rf = 4,75 kΩ, max = 1 A

For each condition, five TS507 operational amplifiers have been measured with the same board. All resistors have an accuracy of 0.1% except for the shunt resistors, which have an accuracy of 1%.

The left part of the figure shows the output voltage versus Isense/Imax. The maximum and minimum theoretical output voltages are shown in red and blue respectively. These have been calculated using *Equation 3 on page 7*. You can see that the output voltage of the operational amplifiers is as predicted between these two trends.

The right part of the figure shows the absolute error on the output voltage versus Isense/Imax. The red trend shows the maximum theoretical error that can occur. As expected, all of our measurements are below this trend. The main error is due to Vio: the lower Vio is, the more accurate the results will be.

Figure 6. Case 1: Rshunt = 3 mΩ, Rg = 100 Ω, Rf = 150 kΩ, Imax = 1 A

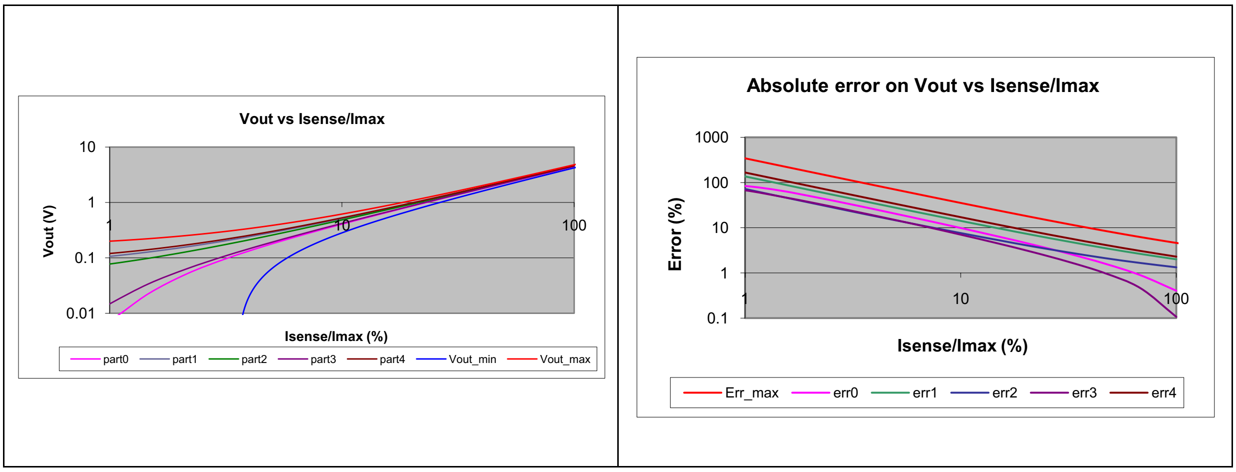


Figure 7. Case 2: Rshunt = 10 mΩ, Rg = 100 Ω, Rf = 47.5 kΩ, Imax = 1 A

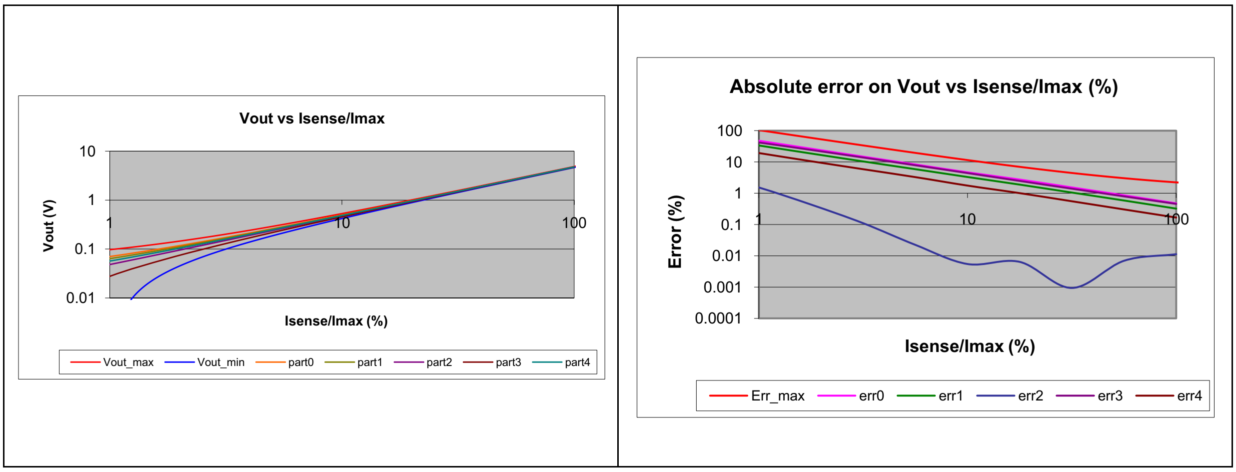


Figure 8. Case 3: Rshunt = 30 mΩ, Rg = 100 Ω, Rf = 16.2 kΩ, Imax = 1 A

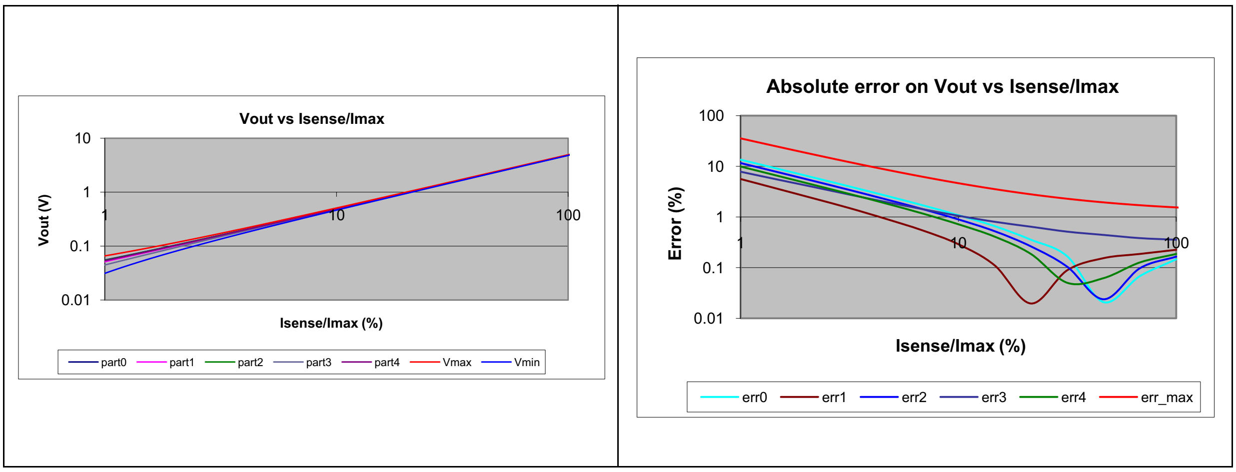
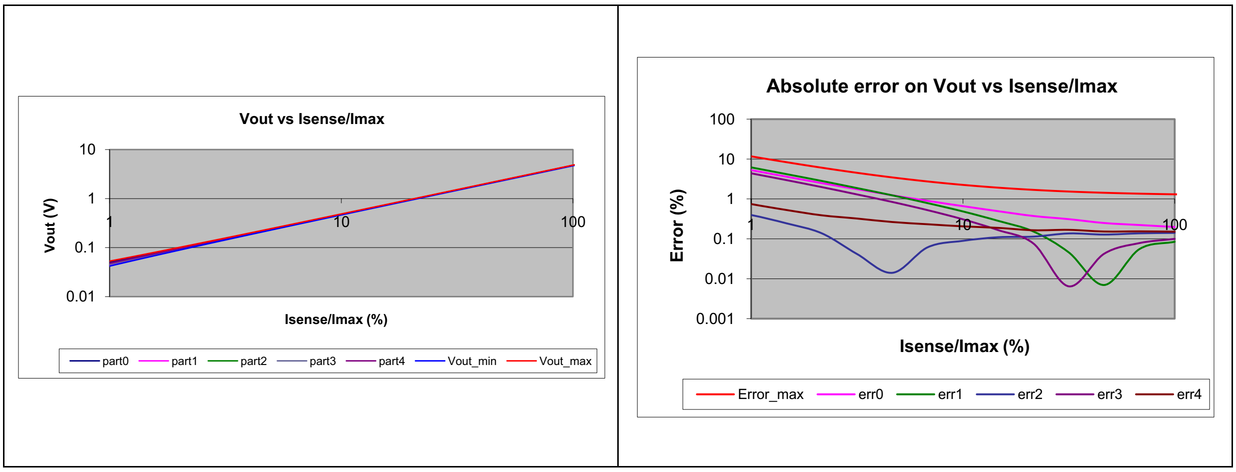


Figure 9. Case 4: Rshunt = 100 mΩ, Rg = 100 Ω, Rf = 4.75 kΩ, Imax = 1 A

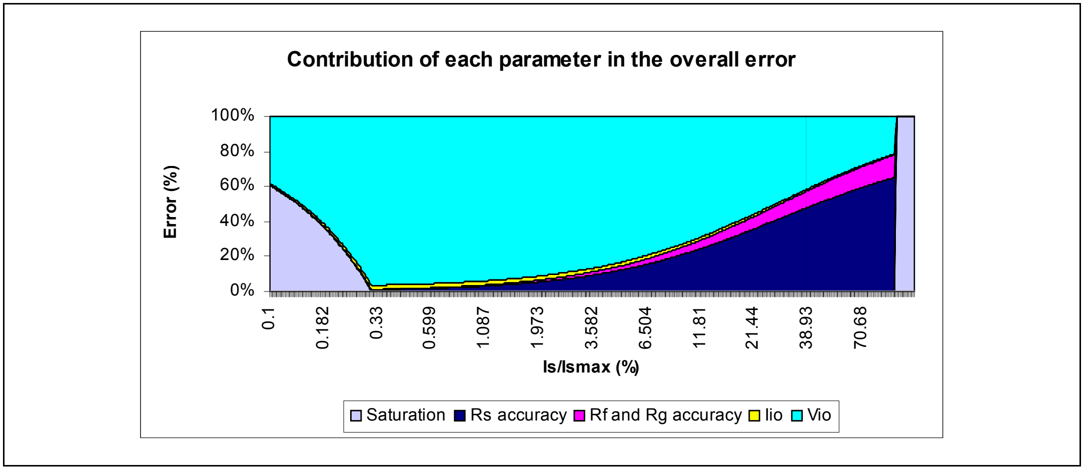


The graphs show that the higher Rshunt is for the same Isense_max, the more accurate the results are. This is due to the fact that if the shunt resistor is small, the schematic gain is high, so Vio is more amplified than with a bigger shunt resistor.

Figure 10 shows the error contribution of each parameter in the overall error for Case 3.

You can see that for a low Isense/Imax the maximum error is due to the saturation. Then, when Isense/Imax increases, the maximum error is caused by the Vio. After this, the most significant error is caused by the inaccuracy of the shunt resistor. To finish, when Isense/Imax is high, you are close to the upper rail of the amplifier, therefore the maximum error contribution is due to the saturation.

Figure 10. Contribution of each parameter in the overall error



The error due to the AVD parameter has not been taken into consideration in these equations, but it is negligible. If the schematic gain equals 162 (in Case 3) and the AVD equals 100 dB, there is an inaccuracy of 0.16%.

The following equation demonstrates this.

Equation 7

$$\frac{Vout}{Vs} = \frac{\frac{Rf}{Rg}}{1 + \frac{Rf}{Rg \cdot AVD}} \quad \text{when} \quad \frac{Rf}{Rg} \ll AVD: \quad \frac{Vout}{Vs} = \frac{\frac{Rf}{Rg}}{1 + \varepsilon} = \frac{Rf}{Rg}(1 - \varepsilon)$$

$$Error = \frac{Rf}{Rg \cdot AVD} \cdot 100\%$$

For example:

Case 3: $\frac{Rf}{Rg} = 162$ AVD = 100 dB

$$Error = \frac{162}{10^5} \cdot 100\% = 0.16\%$$

You can see that the higher the gain of the schematics, the higher the inaccuracy. Nevertheless, the typical AVD for the TS507 equals 131 dB. With this value, the error is divided by more than 35.

6 Frequency behavior

This chapter provides different AC cases permitting the filtering of the measurements.

To sense in a large bandwidth, the gain of the application must not exceed the capability of the amplifier. If the gain is too big, you will be limited by the gain-bandwidth product or by the amplifier's slew rate. As such, for test purposes, we have selected the same conditions as in Case 4 (*Figure 9*).

Rshunt = 100 mΩ Rg = 100 Ω and Rf = 4.75 kΩ

The two first cases deal with the filtering of the measurement for a current source which should be constant. The easiest way to achieve it is to add the capacitor named Cf in *Figure 2*.

In *Figure 11* and *Figure 12*, you can see that the period of oscillations is T = 300 µs, so the frequency equals 3.33 kHz.

The following equation demonstrates how to select the value of Cf to filter the oscillations.

Equation 8

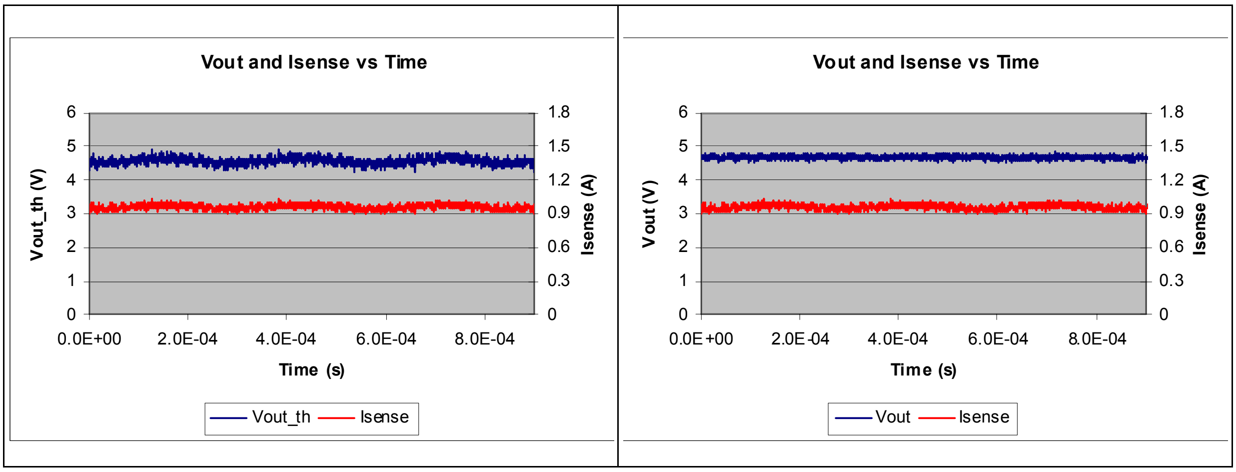
$$F = \frac{1}{2\pi \cdot Rf \cdot Cf} \quad \text{so } Cf = \frac{1}{2\pi \cdot F \cdot Rf} = \frac{1}{2\pi \cdot 3330 \cdot 4750} = 10\ \text{nF}$$

To efficiently cut this frequency, you have to cut one decade earlier, so you have to set Cf to 100 nF.

On the left part of *Figure 11*, the measurement has been performed without the capacitor, and on the right part a capacitor of 100nF has been added. A current of about 1 A is applied.

You can see that the signal is correctly filtered by the capacitor.

Figure 11. Filtering: first example



without capacitor

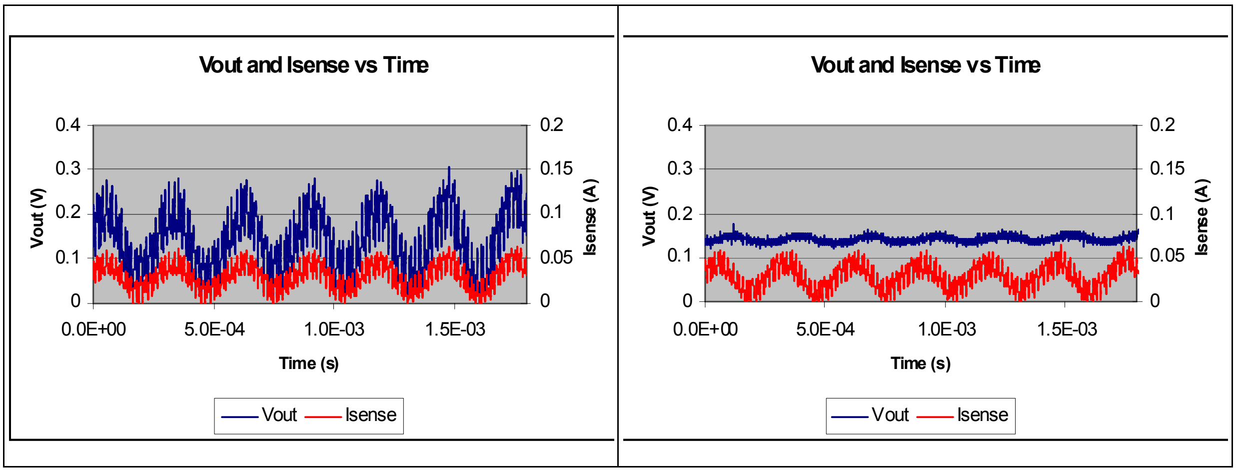
with capacitor: Cf = 100 nf

Figure 12 shows another example with a lower Isense.

Figure 12. Filtering: second example

without capacitor

with capacitor: Cf = 100 nf



As you can see, the signal is filtered. If you increased the capacitor to 1 µF instead of 100 nF you would obtain an even smoother response.

This application note shows the theoretical and practical results, but verifying the behavior with the spice model and, above all, checking the results on bench is recommended.

7 Bill of materials

Table 2. Bill of materials

Part	Footprint	Description	Value	Qty
TS507	SOT23-5	Precision amplifier	TS507	1
Rf	0603	Resistor 0.1%	16.2 kΩ(1)	2
Rg	0603	Resistor 0.1%	100 Ω	2
Rs(2)	2512	Resistor 1%	30 mΩ (1)	1
	9.4 x 9.1 mm	Resistor 1%	30 mΩ (1)	
	Strap	Resistor 1%	30 mΩ (1)	
Cf	0603	Capacitor	1 nF (1)	1
C	0603	Decoupling capacitor	1 µF	1

1. To choose the correct component values, refer to *Chapter 4*. The default value has been chosen for a power source of 5 V, sourcing a maximum current of 1 A.
2. Only one shunt resistor is required, several footprints are available.

8 Conclusion

This document provides the information necessary to develop your low-side current sensing application using the TS507. You can accurately measure current with a limited number of components even if the sense current is noisy. With the theoretical equations provided, you can easily predict the maximum error on the output voltage. To minimize errors, you must select the components correctly according to the parameters described in this application note.

9 Revision history

Table 3. Document revision history

Date	Revision	Changes
25-Oct-2010	1	Initial release.

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