UM1737
User manual

How to use the product evaluation board STEVAL-ISQ014V1 for low-side current sensing with the TSZ121 operational amplifier

Introduction

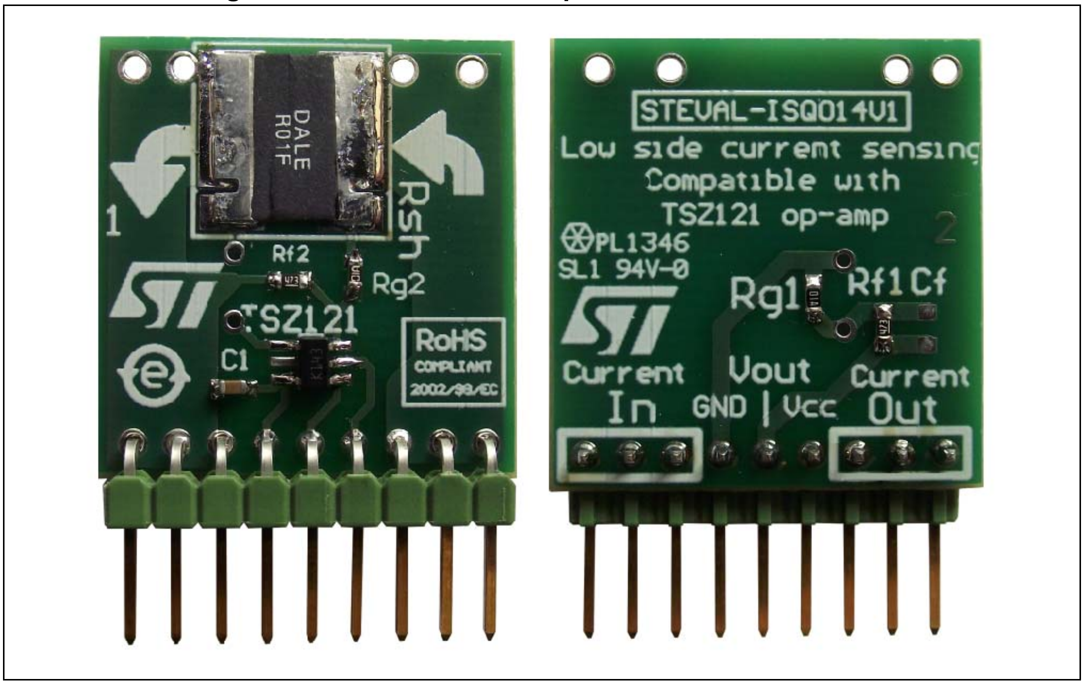
This document describes how to use the product evaluation board STEVAL-ISQ014V1 for low-side current sensing with the TSZ121 operational amplifier (op amp).

Power management mechanisms are found in most electronic systems and power protection is of vital importance for them. One useful method of protecting an application is by sensing the current. The low-side current sensing method consists of placing a sense resistor between the load and the ground of the circuit. The resulting voltage drop is amplified using the TSZ121.

This user manual describes how to accurately measure the current in your application and describes the advantages of the low-side current sensing method. In addition, it provides:

- the schematics of the STEVAL-ISQ014V1 evaluation board
- a method for selecting the most appropriate components for your application
- theoretical and practical results

Figure 1. STEVAL-ISQ014V1 product evaluation board



Contents

1 Advantages of the low-side current sensing method

With the low-side current sensing method, the common mode voltage of the op amp is close to ground, regardless of the voltage of the power source. Therefore, the current voltage that is sensed can be amplified by a low input rail operational amplifier (there is no need for a rail-to-rail input op amp).

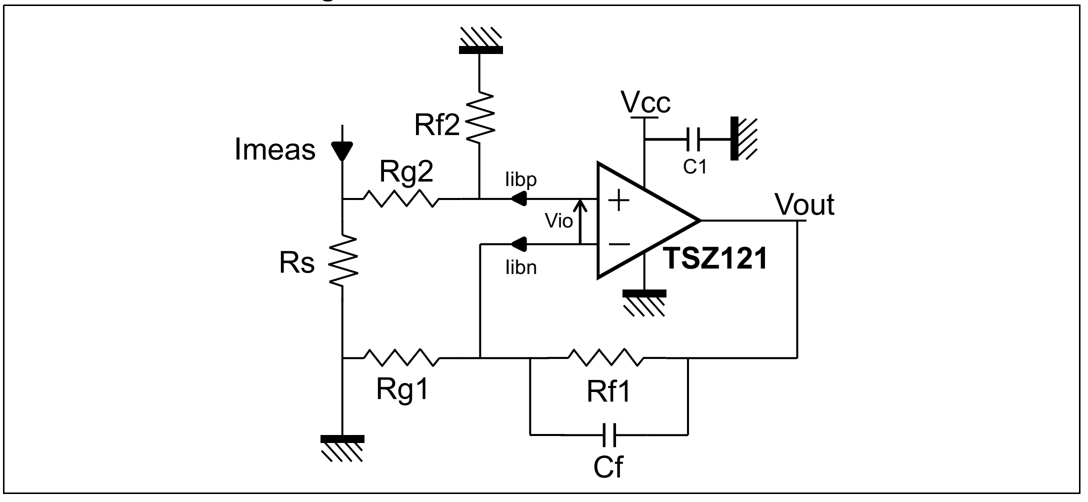
The TSZ121 is a very accurate op amp, which allows you to measure the current through your application precisely with a smaller shunt value. Thus, the dissipated power is also reduced.

If you need to sense the current with the high-side sensing method, STMicroelectronics also provides the appropriate products with the TSC series.

2 STEVAL-ISQ014V1 product evaluation board schematic

Figure 2 shows the STEVAL-ISQ014V1 schematic. The voltage drop through the shunt resistor Rs, created by the current Imeas, is amplified by the TSZ121.

Figure 2. STEVAL-ISQ014V1 schematic



1. Imeas = current, Rs = shunt resistor, Rg, Rf = resistors, Iibp, Iibn = input currents, C = capacitor

The TSZ121 is a very accurate op amp which operates from 1.8 V to 5.5 V. It has a rail-to-rail configuration on both its input and output. At 25 °C, it demonstrates the following features:

- Vio = 5 µV (max)
- AVD = 135 dB
- GBP = 400 kHz
- Vol = 30 mV (max) with Rl = 10 kΩ

Further details on this op amp can be found at *www.st.com*.

3 How to choose the right components for your application

Various component values can be selected for your application. They include:

- Rshunt
- resistors for the amplifier gain

The four steps below describe how 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).

Example

Imax = Power_max/Voltage = 5 W/5 V = 1 A

2. **Find the correct shunt resistor**

This value has to be limited to avoid a significant voltage drop (for example, 1 % of the application voltage) and to limit the power dissipation. It must, however, be high enough to obtain good accuracy.

Example

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

Rshunt x Imax ≤ Vsense max

=> Rshunt ≤ (1 % x 5 V)/1 A

So, Rshunt must be lower than or equal to 50 mΩ. In the current application example, Rshunt has been set to 10 mΩ.

3. **Calculate the maximum power dissipation in the shunt resistor**

To avoid damaging the shunt resistor itself, the shunt resistor has to sustain a suitable wattage.

Example:

Pmax = Rshunt x I^2 = 0.01 x 1^2 = 0.01 W

Another advantage of using the high accuracy TSZ121 op amp is that it allows you to amplify small signals while maintaining a good signal-to-noise ratio. Thus, the power dissipation is limited and the shunt resistor price is reduced.

4. **Choose the appropriate configuration gain**

Vout = (Rf/Rg) x Rshunt x I

To avoid saturation: Vout ≤ Voh => Rf < (Voh x Rg)/(Rshunt x Imax)

In the current application configuration, Rg = 100 Ω and Voh = 4.970 V (TSZ121 at 25 °C, Vcc = 5 V).

Therefore, Rf max = (4.970 x 100)/(0.01 x 1) = 49.7 kΩ

Consequently, Rf must be lower than 49.7 kΩ to avoid saturation of the TSZ121 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 E24 series leads to an Rf of 47 kΩ.

To minimize the offset caused by the input currents, the feedback resistors must be minimized. The higher the Rf, the higher the error due to Iio (see *Section 4.1: Theoretical measurements*). An Rg of 100 Ω must be considered (the lower Rg, the lower Rf) but, Rf should not be so low that the output saturation voltages cannot be increased.

Note: If the accuracy obtained is not sufficient, go back to step 2 and increase the Rshunt value.

4 Theoretical and practical measurements

4.1 Theoretical measurements

Cf can be ignored for the DC analysis.

Equation 1 can be calculated using *Figure 2* as a reference for the components.

Equation 1

$$\mathrm{Vout} = \mathrm{Rs} \times \mathrm{I} \times \left(1 - \frac{\mathrm{Rg2}}{\mathrm{Rg2} + \mathrm{Rf2}}\right) \times \left(1 + \frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right) + \mathrm{Iibp} \times \left(\frac{\mathrm{Rg2} \times \mathrm{Rf2}}{\mathrm{Rg2} + \mathrm{Rf2}}\right) \times \left(1 + \frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right) - \mathrm{Iibn} \times \mathrm{Rf1} - \mathrm{Vio} \times \left(1 + \frac{\mathrm{Rf1}}{\mathrm{Rg1}}\right)$$

Equation 1 can be simplified as *Equation 2* assuming that Rf2 = Rf1 = Rf and Rg2 = Rg1 = Rg.

Equation 2

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

Thanks to the good matching of resistors Rf and Rg on the inputs, Iib has no affect on Vout.

In *Equation 2*, the only error remaining is due to Vio and Iio. The Iio represents the input offset current (Iio = Iibp - Iibn) and the Vio represents the input offset voltage. To obtain a precision current sensing solution, the Vio should be as low as possible. For the TSZ121, Vio is equal to 5 µV max which corresponds to a very high accuracy.

Considering the errors due to resistor inaccuracy, *Equation 3* is obtained.

Equation 3

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

Where:

Vth = Rs x I x (Rf/Rg)

ΔR/R is the resistance tolerance. In the current application example, the tolerance of Rg and Rf is 0.1 % and that of Rshunt is 1 %.

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

Equation 4

$$Vth\left(\frac{\Delta Rs}{Rs} + \frac{Rf}{Rf+Rg}\left(\frac{\Delta Rf1}{Rf1} + \frac{\Delta Rg1}{Rg1}\right) + \frac{Rg}{Rf+Rg}\left(\frac{\Delta Rf2}{Rf2} + \frac{\Delta Rg2}{Rg2}\right)\right) = Vth(2\varepsilon_1 + \varepsilon_2)$$

Equation 3 can be simplified as *Equation 5*

Equation 5

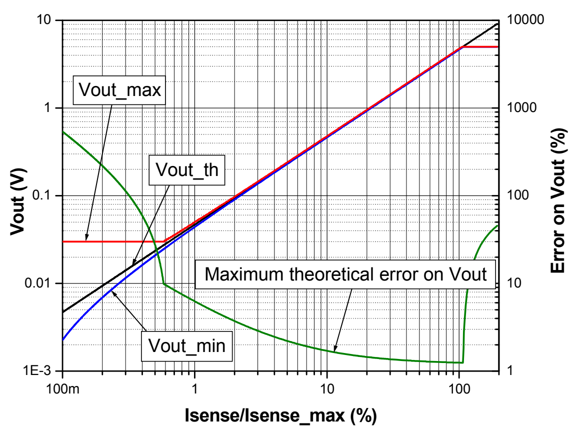
$$Vout = Vth(1 + 2\varepsilon_1 + \varepsilon_2) + Rf \times Iio - Vio\left(1 + \frac{Rf}{Rg}\right)$$

Figure 3 shows the theoretical behavior of the above defined application.

Vout_th, Vout_min, and Vout_max are referred to the left Y-axis.

Vout_min and Vout_max take into consideration the Voh and Vol errors due to input currents, Vio, and resistor inaccuracy. In practice, the measured values should be between the Vout_min and Vout_max curves.

Figure 3. Theoretical output voltage and error vs. Is/Imax



The maximum theoretical error on the output voltage (shown in green) is referred to the right Y-axis and is defined in *Equation 6*.

Equation 6

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

Example:

If Imax = 1A with the same conditions on the resistors as shown in *Figure 3*, the following applies:

- For Isense = 10 mA, Isense/Imax = 1 %, the maximum error on the measured voltage is lower than 7 %.
- For Isense = 70 mA to 1 A (7 % to 100 % of Imax), the maximum error on the measured voltage is lower than 2 %.

Note: When Isense is used at 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 2 x 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 TSZ121 while applying the methods described in this user manual.

Table 1. Maximum error on the measured value (depending on Imax) for the TSZ121

Imax (A)	Rs (Ω) ε = 1 %	Rg (Ω) ε = 0.1 %	Rf (kΩ) ε = 0.1 %	Maximum absolute error (%)				
				Isense/Imax 1 %	Isense/Imax 3 %	Isense/Imax 10 %	Isense/Imax 30 %	Isense/Imax 100 %
1	0.05	100	9.76	2.2	1.5	1.3	1.2	1.2
2	0.02	100	12.1	2.5	1.6	1.3	1.2	1.2
3	0.01	100	16.2	2.9	1.8	1.4	1.3	1.2
4	0.01	100	12.1	2.5	1.6	1.3	1.2	1.2
5	0.01	100	9.76	2.2	1.5	1.3	1.2	1.2
7	0.005	100	14	2.7	1.7	1.3	1.2	1.2
10	0.005	100	9.76	2.2	1.5	1.3	1.2	1.2
12	0.003	100	13.3	2.6	1.7	1.3	1.2	1.2
15	0.003	100	10.7	2.3	1.6	1.3	1.2	1.2
20	0.002	100	12.1	2.5	1.6	1.3	1.2	1.2

Rs is calculated for a maximum sense voltage of 50 mV. It represents 1 % of the voltage drop for a 5 V voltage source.

4.2 Practical measurements

This section summarizes the results of several practical measurements:

- Case 1, use of the TSZ121 op amp which has a maximum Vio of 5 µV for Vcc = 5 V and Vicm = 2.5 V (see *Figure 4* and *Figure 5*).
- Case 2, use of another op amp which has a maximum Vio of 1 mV (see *Figure 6* and *Figure 7*)

In both cases, five devices were measured on different boards using the following component values:

- Rshunt = 10 mΩ
- Rg = 100 Ω
- Rf = 47 kΩ
- Imax = 1 A

All resistors had an accuracy of 0.1 % except for the shunt resistors which had an accuracy of 1 %.

Figure 4 and *Figure 6* show the output voltage versus Isense/Imax (100 % means that Isense = Imax = 1 A). The maximum and minimum theoretical output voltage trends are shown in red and blue respectively. These have been calculated using *Equation 3*. The output voltage of the op amps is, as predicted, between these two trends.

Figure 5 and *Figure 7* show the absolute error on the output voltage versus Isense/Imax. The red trend shows the maximum theoretical error that can occur. As expected, all ST measurements are below this trend. The main error contribution is due to the Vio i.e. the lower Vio is, the more accurate the results are. This is why it is important to use a very accurate op amp such as the TSZ121.

Figure 4 and *Figure 5* show that thanks to the TSZ121, it is possible to highly reduce the inaccuracy on the current measurement. This is especially true when there is a small signal that has to be amplified (because with the signal amplification, an error due to the amplification of the Vio is added).

Figure 4. Output voltage vs. Isense/Imax using the TSZ121

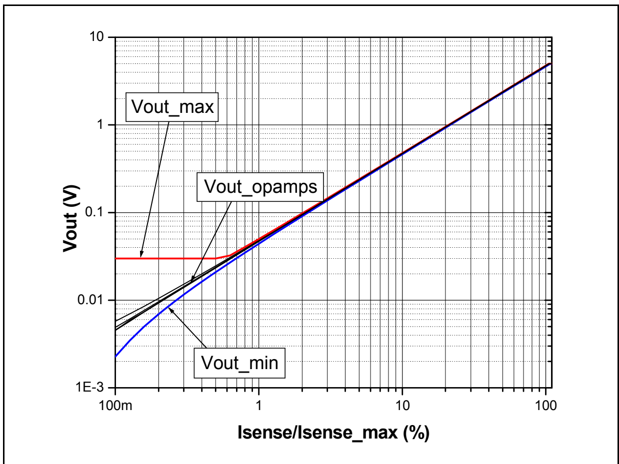


Figure 5. Absolute error on the output voltage vs. Isense/Imax using the TSZ121

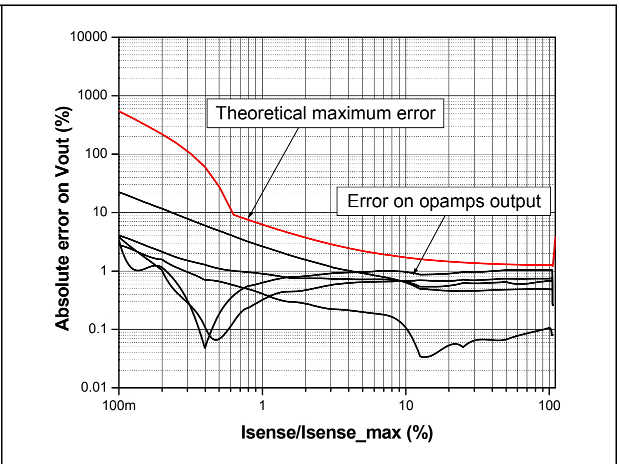


Figure 6. Output voltage vs. Isense/Imax using an alternative op amp

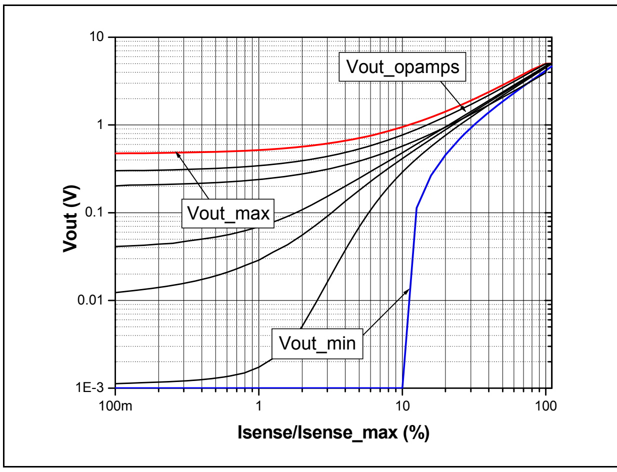


Figure 7. Absolute error on the output voltage vs. Isense/Imax using an alternative op amp

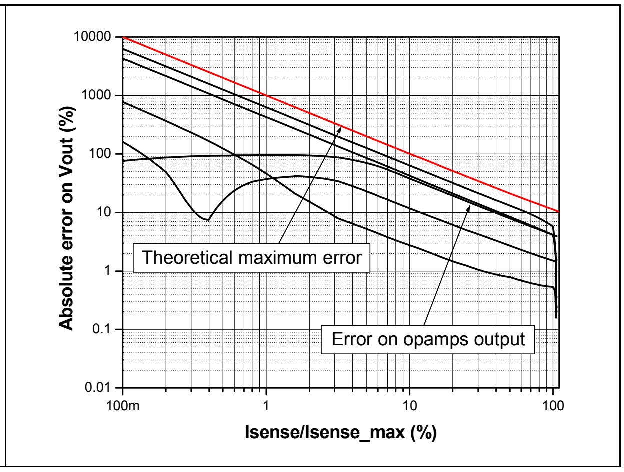


Figure 8 and *Figure 9* show the error contribution of each parameter to overall error for case 1 and case 2.

For a low Isense/Isense_max the error is mainly due to the saturation. When Isense/Isense_max increases, the error is mainly caused by the Vio. After this, the most significant error contribution is caused by the inaccuracy of the shunt resistor. Finally, when Isense/Isense_max is high, close to or above the upper rail of the amplifier, the maximum error contribution is the saturation.

Figure 8. Contribution of each parameter to overall error for the TSZ121

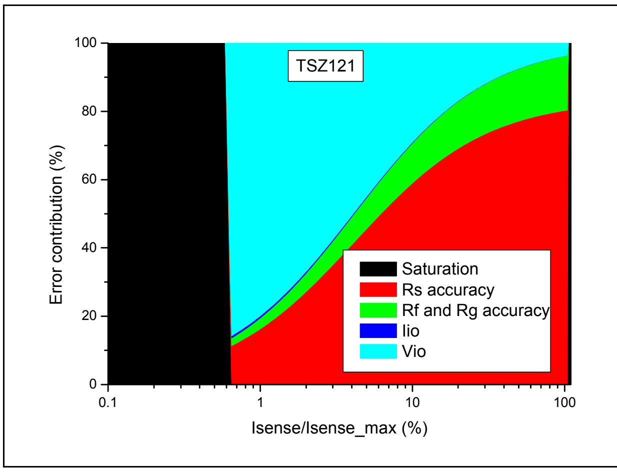
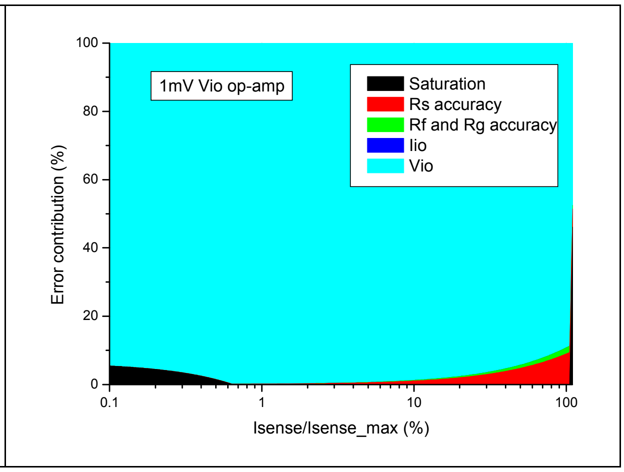


Figure 9. Contribution of each parameter to overall error for a 1 mv Vio op amp



The error due to the AVD parameter has not been taken into consideration in this document, because it is negligible. If the schematic gain equals 470 (gain used for the measurements) and the AVD equals 120 dB, there is an inaccuracy of 0.047%.

Equation 7 demonstrates this.

Equation 7

$$\frac{Vout}{Rs \times I} = \frac{\frac{Rf}{Rg}}{1 + \frac{1 + \frac{Rf}{Rg}}{AVD}}$$

When:

Rf/Rg << AVD

$$\frac{Vout}{Rs \times I} = \frac{\frac{Rf}{Rg}}{1 + \varepsilon} \approx \frac{Rf}{Rg}(1 - \varepsilon)$$

$$Error(\%) = -\frac{1 + \frac{Rf}{Rg}}{AVD} \times 100$$

Example:

Rf/Rg = 470

AVD = 120 dB (the minimum value for the TSZ121)

$$Error = -\frac{1 + \frac{Rf}{Rg}}{AVD} \times 100 = -0.047\%$$

Clearly, the higher the gain of the schematics, the higher the inaccuracy, but in this case the error is negligible.

5 Frequency behavior

This section describes how the measurements are filtered.

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, the application is limited by the gain-bandwidth product or by the slew rate of the amplifier. For test purposes, the same conditions as for DC measurements are selected:

Rshunt = 10 mΩ, Rg = 100 Ω, and Rf = 47 kΩ.

This example deals with filtering the measurement of an AC current source which has overlapping oscillations. The easiest way to achieve overlapping oscillations is to add a capacitor e.g. see the Cf capacitor in *Figure 2*.

Figure 10 and *Figure 11* show that the period of oscillations is T = 300 µs. In order to efficiently filter 3.3 kHz, we can cut by a factor of ten earlier, and thus choose fc = 330 Hz.

Thus, choose:

$$Cf = \frac{1}{2\pi \times f_c \times R_f} = \frac{1}{2\pi \times 330 \times 47000} = 10nF$$

In *Figure 10*, the measurement was performed without the capacitor.

In *Figure 11* a capacitor of 10 nF was added. An AC current from 0.4 A to 1 A was then applied. The signal is correctly filtered by the capacitor and the overlapping oscillations on the current source are no longer visible on the op amp output voltage.

Figure 10. Filtering without the Cf capacitor

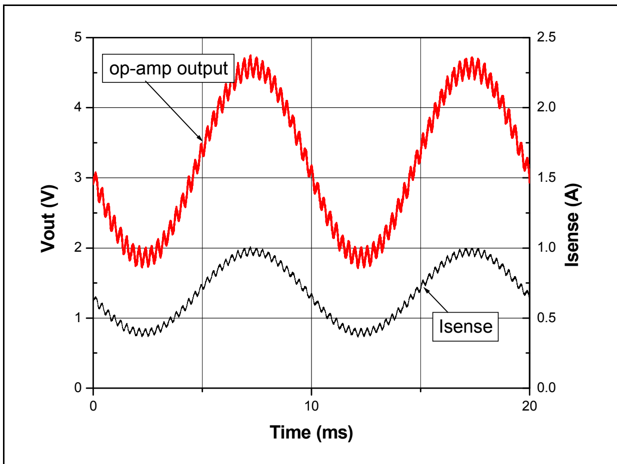
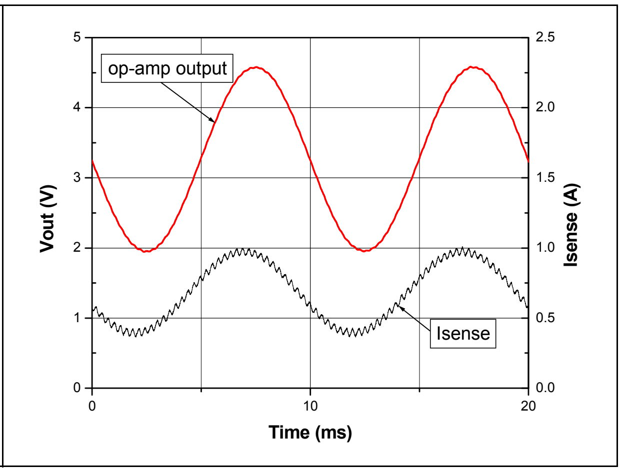


Figure 11. Filtering with Cf capacitor = 10 nF



Note: Verification of this behavior with the spice model and, above all, checking the results on the bench is recommended.

6 Bill of materials

Table 2. Bill of materials

Part	Footprint	Description	Value	Qty
TSZ121	SOT23-5	Very high accurate amplifier	TSZ121ILT	1
Rf	0603	0.1 % resistor	47 kΩ(1)	2
Rg	0603	0.1 % resistor	100 Ω	2
Rs	9.4 x 9.1 mm	1 % 4-terminal shunt resistor	10 mΩ(1)	1
Cf	0603	Capacitor	33 nF	1
C1	0603	Decoupling capacitor	22 nF	1

1. To choose the correct component values, refer to *Section 3*. The default value has been chosen for a power source of 5 V, sourcing a maximum current of 1 A

7 Conclusion

This document provides the information necessary to develop a low-side current sensing application using the TSZ121. You can accurately measure current with a limited number of components even if the sense current is noisy. Moreover, using the TSZ121 high precision op amp allows you to reduce the shunt resistor value and to increase the schematic gain without losing accuracy. Thanks to a lower shunt value, there is a lower dissipated power within the shunt resistor. Consequently, the shunt resistor’s size can be reduced and the customer can save money.

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 *Section 3*.

8 Revision history

Table 3. Document revision history

Date	Revision	Changes
23-May-2014	1	Initial release