

Adjustable gain with a current sensing

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Introduction

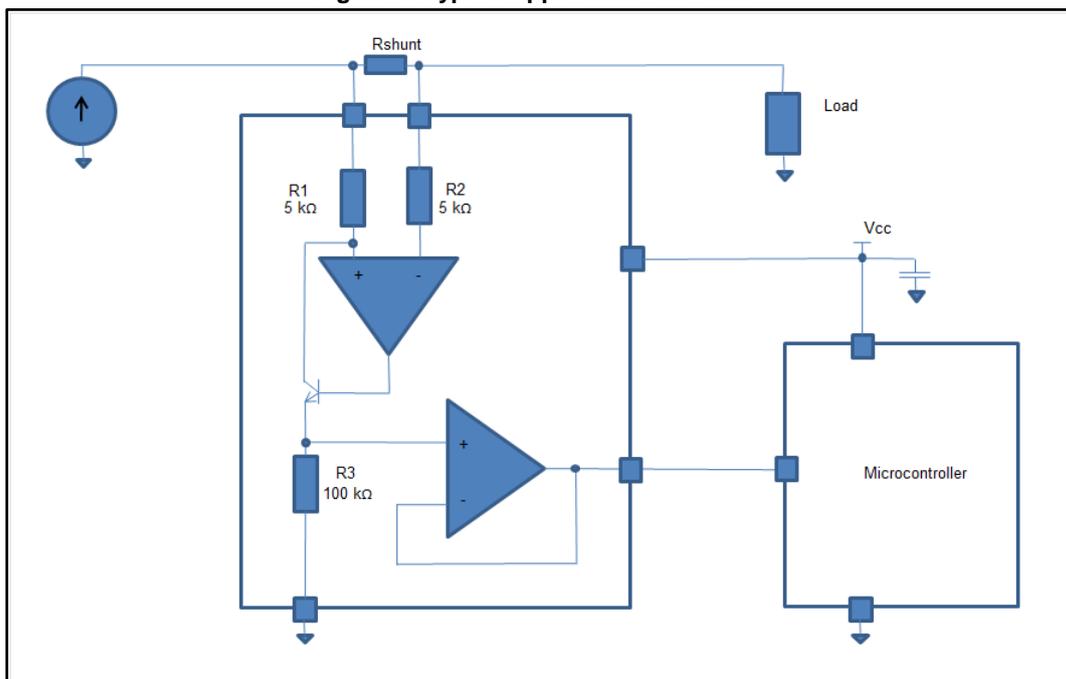
This application note explains how to use current sensing amplifiers with series resistors on the sense inputs. This approach is especially useful for applications where the gain must be adjusted.

When the current sensing amplifier is powered from a single-supply, $V_{CC} = 5\text{ V}$, it can amplify differential input signals at a common-mode voltage well beyond the power supply rail. This common-mode voltage, in a current-sense amplifier such as the TSC101, can rise to 28 V and can rise even higher in the TSC103. The device amplifies small voltages across a shunt resistor on the high-voltage rail and feeds it to a low-voltage ADC generally embedded in a microcontroller. The output voltage is proportional to the voltage drop measured on the sense resistor.

The current sensing of the TSC series has a dedicated fixed gain that can be 20 V/V, 25 V/V, 50 V/V, or 100 V/V. The gain is given by the ratio $R3/R1$.

Figure 1 illustrates a typical application schematic.

Figure 1: Typical application schematic



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1 Internal resistances

Internally, the resistances are extremely well matched, meaning we can consider the ratios of the actual values of R1, R2, and R3 over their respective targeted values to be identical. Nevertheless, R1, R2, and R3 values vary from one TSC product to another due to process variation and temperature.

The value of the resistance over temperature is defined by the following formula: $R(1 + TC \cdot \Delta T)$, where TC is the temperature coefficient and ΔT is $T_{amb} - 25$ °C.

If we take the temperature coefficient into account, we have:

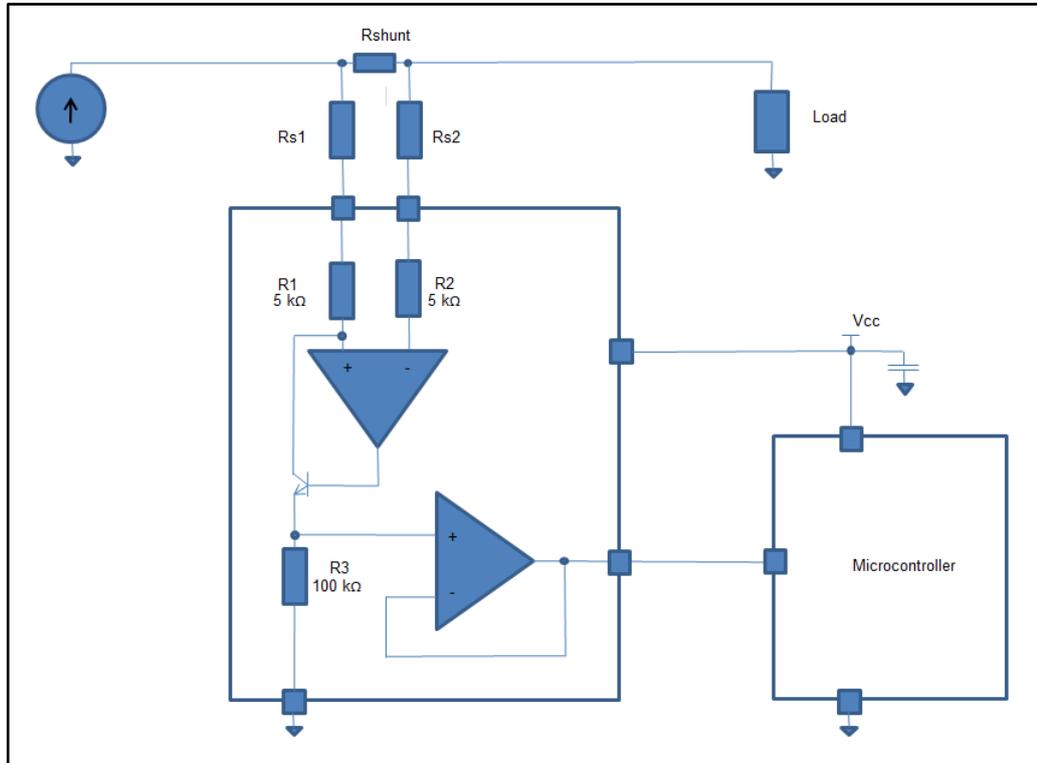
$$G = \frac{R3(1 + TC\alpha * \Delta T)}{R1(1 + TC\alpha * \Delta T)}$$

As R3 and R1 are made of the same material, they have the same TC: $G = R3/R1$. Therefore, the gain is related only to the ratio of R3 and R1. In other words, the gain is independent of process variation and temperature. The final gain is well controlled and can easily be trimmed during manufacturing.

2 Performance with input series resistors

In some applications, the gain of the current sensing has to be different from the one available with our IC (20 V/V, 25 V/V, 50 V/V, or 100 V/V). This gain can be fine-tuned by adding external serial resistances R_{s1} and R_{s2} (see [Figure 2](#)). Note that adding external components modifies the $R3/R1$ ratio and introduces gain error.

Figure 2: Principle schematic



3 Temperature coefficient error

When series resistors R_{s1} and R_{s2} (R_{si}) are inserted into the application, the output voltage equation (see [Section 2: "Internal resistances"](#)) is changed. It becomes critical to determine the impact of these resistors on accuracy. The temperature coefficient, $TC\beta$, is different from the temperature coefficient of the internal resistance, $TC\alpha$, because the external resistors are likely made of different material to the internal ones. In this case, the gain is expressed as follows:

$$G = \frac{R3(1 + TC\alpha * \Delta T)}{R1(1 + TC\alpha * \Delta T) + R_{s1}(1 + TC\beta * \Delta T)}$$

$$G \approx \frac{R3}{R1 + R_{s1}} * \left(1 - \frac{R_{s1}}{R1 + R_{s1}} (TC\beta - TC\alpha) * \Delta T \right)$$

And so, due to the different temperature coefficients, gain error (%) is represented by:

$$100 * \frac{R_{s1}}{R1 + R_{s1}} (TC\beta - TC\alpha) * \Delta T$$

Example (see also [Figure 3](#)):

$R1 = 5 \text{ k}\Omega$

$R3 = 100 \text{ k}\Omega$

$TC\alpha = 0.7 \text{ \%/}^\circ\text{C}$ (typical value considered for TSC series)

$TC\beta = 100 \text{ ppm/}^\circ\text{C}$

Figure 3: Gain error due to different temperature coefficients between external and internal resistances

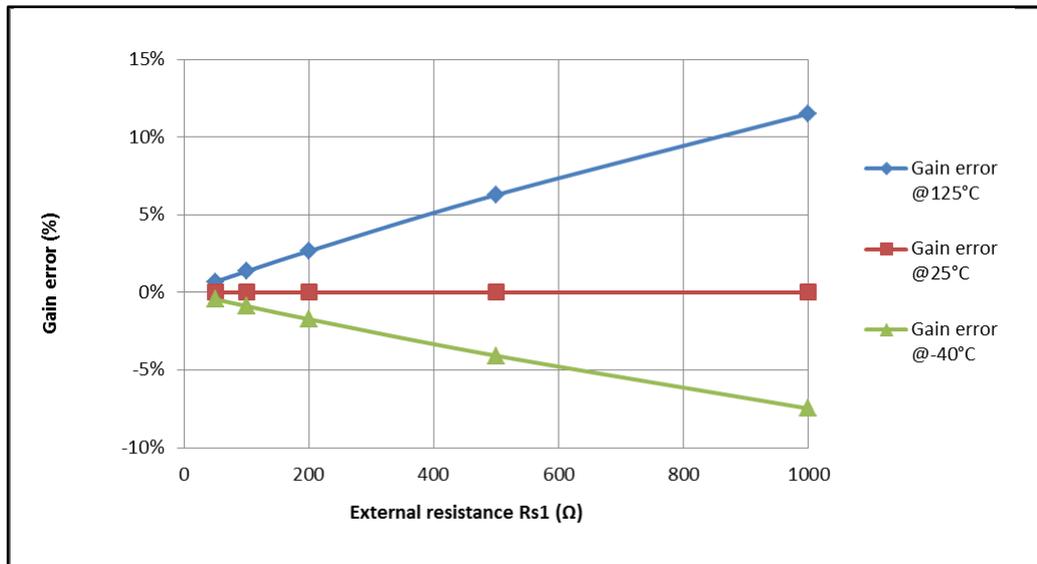


Figure 3 shows that the gain is higher at high temperatures and lower at low temperatures. It is important to make sure R_{si} are as low as possible to limit the error on the gain. Consequently, it is better to choose a TSC product which has the closest gain for the objective required. For example, do not use a 100 V/V product, if you want to obtain a gain of 22 V/V. In this case, choose a product with a gain of 25 V/V.

4 Gain error between two TSC products from different batches

Even if the internal resistances are well matched and with a value around 5 kΩ, the gain may vary from one TSC product to another by as much as ±20 %. This is due to process variation as shown in the equation below:

$$G = \frac{V_{out}}{V_{sense}} = \frac{R3(1 + \varepsilon\alpha)}{R1(1 + \varepsilon\alpha) + Rs1(1 + \varepsilon\beta)}$$

Where:

- $\varepsilon\alpha$ is the precision of internal resistances up to ±20 %
- $\varepsilon\beta$ is the precision of the external resistances

So,

$$G \approx \frac{R3}{R1 + Rs1} * \left(1 - \frac{\varepsilon\beta - \varepsilon\alpha}{1 + \frac{R1}{Rs1}} \right)$$

Consequently, the error on the gain (%) is represented by:

$$-100 * \frac{\varepsilon\beta - \varepsilon\alpha}{1 + \frac{R1}{Rs1}}$$

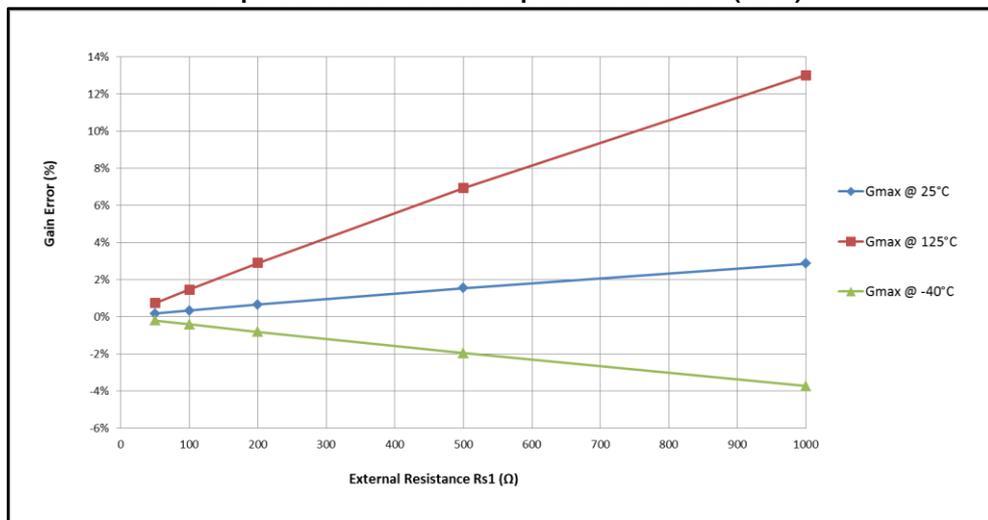
[Table 1](#) gives an example at 25 °C.

Table 1: Gain error vs. series resistor Rs1

Rs1 (Ω)	Theoretical gain	Gain considering process variation ($\varepsilon\alpha = 20\%$) and Rs1 ($\varepsilon\beta = -1\%$)	Gain error (%)
50	19.80	19.84	0.21
100	19.60	19.68	0.41
200	19.23	19.38	0.80
500	18.18	18.52	1.87
1000	16.67	17.25	3.38

Obviously, when the device is used over temperature, both the process variation and the temperature coefficient should be taken into account. In this case, the total error on the gain is shown in [Figure 4](#).

Figure 4: Gain error by the implementation of external resistances, taking into account temperature coefficient and process deviation (20 %)



5 Impact of the Rs1 and Rs2 mismatch

When adding the external resistances R_{si} , it is necessary to fine-tune the gain. This is because the input bias current is the same on pin+ and pin- and it is extremely important to have the same resistances connected to the V_n and V_p pins so as to avoid creating a big equivalent input offset voltage. However, due to the precision of the external resistors this equivalent offset exists as shown in the equation below:

$$V_{io} = (R_1 + R_{s1}(1 + \epsilon\beta))I_{ib} - (R_2 + R_{s2}(1 + \epsilon\beta))I_{ib}$$

So,

$$V_{io} \approx 2 * \epsilon\beta * I_{ib} * R_{s1}$$

Where: $\epsilon\beta$ is the precision of the added serial resistances R_{si} .

Example:

- $R_1 = R_2 = 5 \text{ k}\Omega$
- $R_3 = 100 \text{ k}\Omega$
- $I_{ib} = 15 \mu\text{A}$

In the following table, the gain of the TSC product is 20 V/V, 50 V/V, or 100 V/V. It has been fine-tuned thanks to the R_{si} resistances (whose precision is 1 %). The calculus of the V_{out} offset has taken into account a process variation of 20 % on the internal resistors which possibly contribute to a higher gain.

Table 2: V_{out} offset at different gain vs. series resistances R_{si}

R_{s1+2} (Ω)	R_{s1} (Ω)	R_{s2} (Ω)	Equivalent V_{io} (V)	V_{out} offset (V) with $G = 20$	V_{out} offset (V) with $G = 50$	V_{out} offset (V) with $G = 100$
50	50.5	0	7.58E-04	1.50E-02	3.76E-02	7.51E-02
		49.5	1.50E-05	2.97E-04	7.44E-04	1.49E-03
100	101	0	1.52E-03	2.98E-02	7.45E-02	1.49E-01
		99	3.00E-05	5.90E-04	1.48E-03	2.95E-03
200	202	0	3.03E-03	5.86E-02	1.47E-01	2.93E-01
		198	6.00E-05	1.16E-03	2.90E-03	5.80E-03
500	505	0	7.58E-03	1.40E-01	3.49E-01	6.99E-01
		495	1.50E-04	2.77E-03	6.92E-03	1.38E-02
1000	1010	0	1.52E-02	2.59E-01	6.48E-01	1.30E+00
		990	3.00E-04	5.14E-03	1.28E-02	2.57E-02

To this equivalent V_{io} , the V_{io} of the TSC itself should be added. Error in gain and temperature seen in previous parts of this document should also be considered.

6 Overall error

This application note summarizes the error terms on the gain and V_{out} by adding serial resistors on the V_n and V_p pins. It does not take into account the output voltage accuracy described in the TSC datasheets because this parameter is always applicable (with or without serial resistances on the inputs).

The following example (for the TSC103) considers the overall error i.e. all error due to process variation and the temperature coefficient. The mismatch for $V_{sense} = 50$ mV.

- $V_{sense} = 50$ mV
- Internal gain (G) = 20 but, with the addition of R_{s1} , $G = 500 \Omega$ and theoretical gain is = 18.18 V/V
- Temperature = 125 °C
- Process variation = 20 %
- R_{s1} precision = ± 1 %
- Temperature coefficient of internal resistance = 0.7 %/°C
- Temperature coefficient of external resistance = 100 ppm/°C

The gain error due to the temperature coefficient is:

$$\varepsilon_{TC} = \frac{R_{s1}}{R1 + R_{s1}} (TC\beta - TC\alpha) * \Delta T$$

$$\text{So, } \varepsilon_{TC} = 6.27 \%$$

The gain error due to process variation is:

$$\varepsilon_{PV} = \frac{\varepsilon\beta - \varepsilon\alpha}{1 + \frac{R1}{R_{s1}}}$$

$$\text{So, } \varepsilon_{PV} = 1.87 \%$$

The total gain error is:

$$\varepsilon_G \approx \varepsilon_{TC} + \varepsilon_{PV}$$

$$\text{So, } \underline{\varepsilon_G = 8.14 \%}$$

The error on V_{out} due to gain error (i.e. the error on the output) is:

$$\epsilon V_{og} = G * \epsilon G * V_{sense}$$

$$\text{So, } \epsilon V_{og} = 18.18 \text{ V/V} * 8.14 \% * 50\text{e-}3 \text{ V} = 74 \text{ mV}$$

The error due to the mismatch of the external resistances R_{si} is:

$$\epsilon V_{io} = (R1 + R_{s1}(1 + \epsilon\beta))I_{ib} - (R2 + R_{s2}(1 + \epsilon\beta))I_{ib}$$

$$\text{So, } \epsilon V_{io} = 0.15 \text{ mV}$$

The error on the output voltage is:

$$\epsilon T_{ot} = \epsilon V_{og} + \epsilon V_{io} * G$$

$$\text{So, } \underline{\epsilon T_{ot} = 77 \text{ mV}}$$

This result shows that, at 125 °C, an added resistance of 500 Ω (representing temperature coefficient, process variation, and mismatch) can add an error up to 77 mV on the output voltage compared to the theoretical V_{out} . The inherent error of the TSC103, which has a gain accuracy of 4 %, must also be taken into account when calculating the total error on the output voltage.

7 Conclusion

To decrease the gain, use the products TSC101, TSC1021, and TSC103. Choose the product with the closest gain for the objective required (which is above the targeted value) and add two similar resistors in series with the inputs. To minimize the impact of the gain modifications on the accuracy of the TSC product, make sure that the:

- value of the external resistance, R_s , is as low as possible
- resistances on the V_p and V_n input pins are matched

To increase the gain use the TSC1031 as a resistance can also be added on the R3 pin. All the issues explained above which relate to the temperature coefficient, process variation, and V_{io} offset, remain the same.

8 Revision history

Table 3: Document revision history

Date	Revision	Changes
29-Nov-2013	1	Initial release
16-Dec-2016	2	Updated resistors of Figure 1 and Figure 2

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