Exploring current sense amplifiers

STMicroelectronics Tech days

Error source acting as a percentage

Chapter 8

- Gain error
- Linearity

User guide

This presentation provides a written explanation of the topic covered in the eighteenth chapter of the video: **“Error source acting as a percentage #8”**, which is available on our YouTube channel at the following link:

Video on YouTube

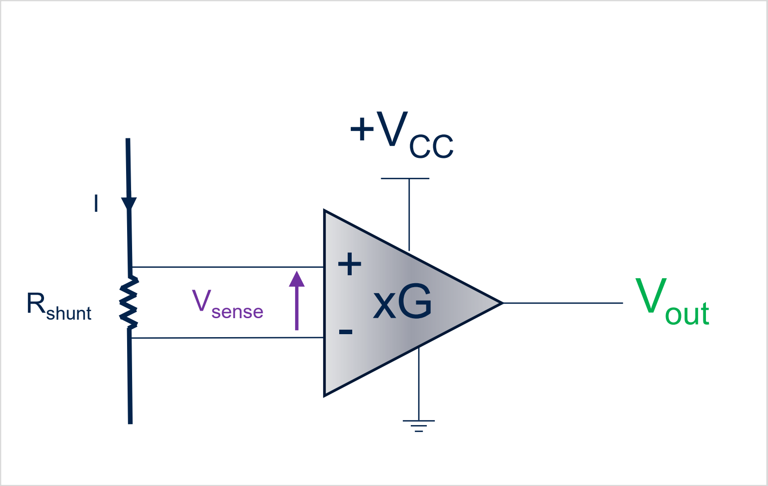
Recommendations

In this document you’ll find key concepts explained through informative tables, graphs, sequences of graphs, followed by a detailed explanation.

- When you see this icon: Explanation the topic is explained in detail on the following page(s)
- Each explanation page shows the page or page range where the topic is explained: (page # to #)
- If you see this icon: Continue the explanation continues on the next page(s)

Gain error: what is it?

Gain error



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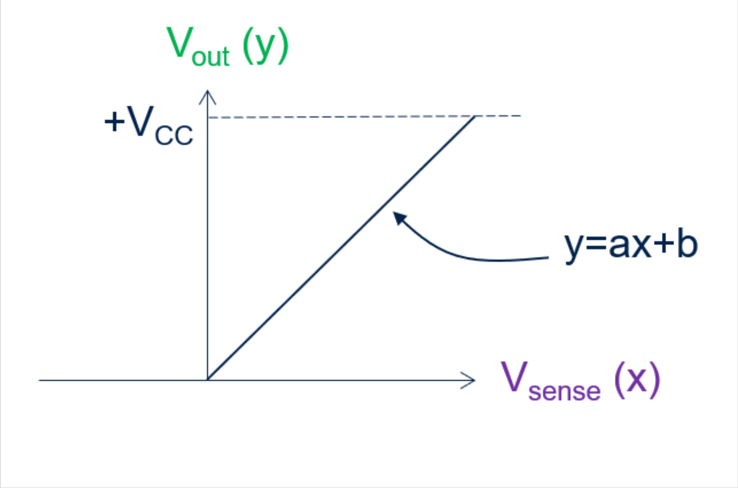

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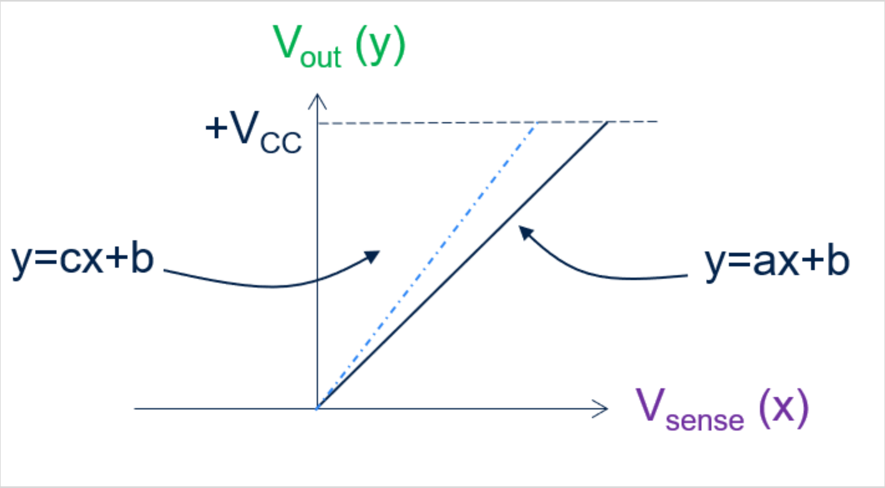


TSC2010 series

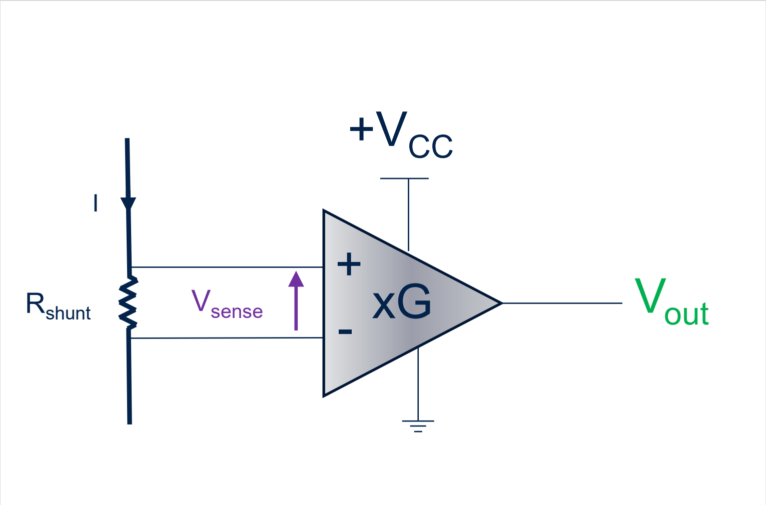
Eg	Gain error vs. temperature	ΔV_{out} = 100 mV to (V_{cc} - 100 mV) $T_{min} < T < T_{max}$			0.3 0.3	%

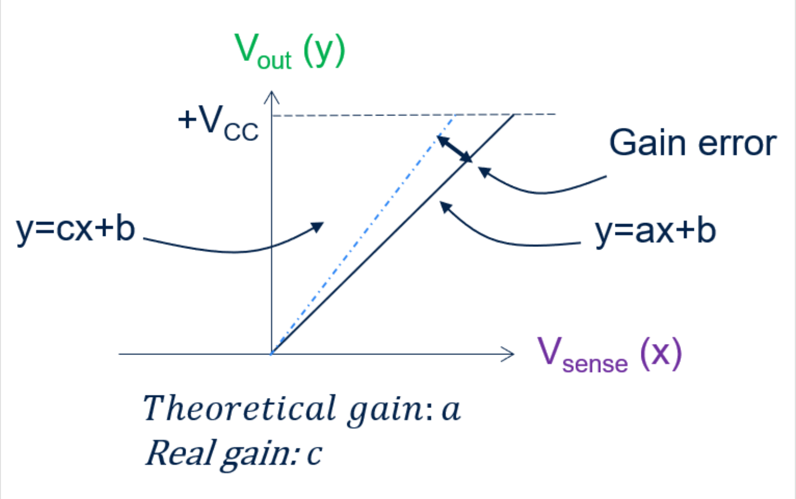
Explanation

Gain error: what is it?

Gain error

3





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Explanation

Gain error: what is it?

Explanation of pages 4–5

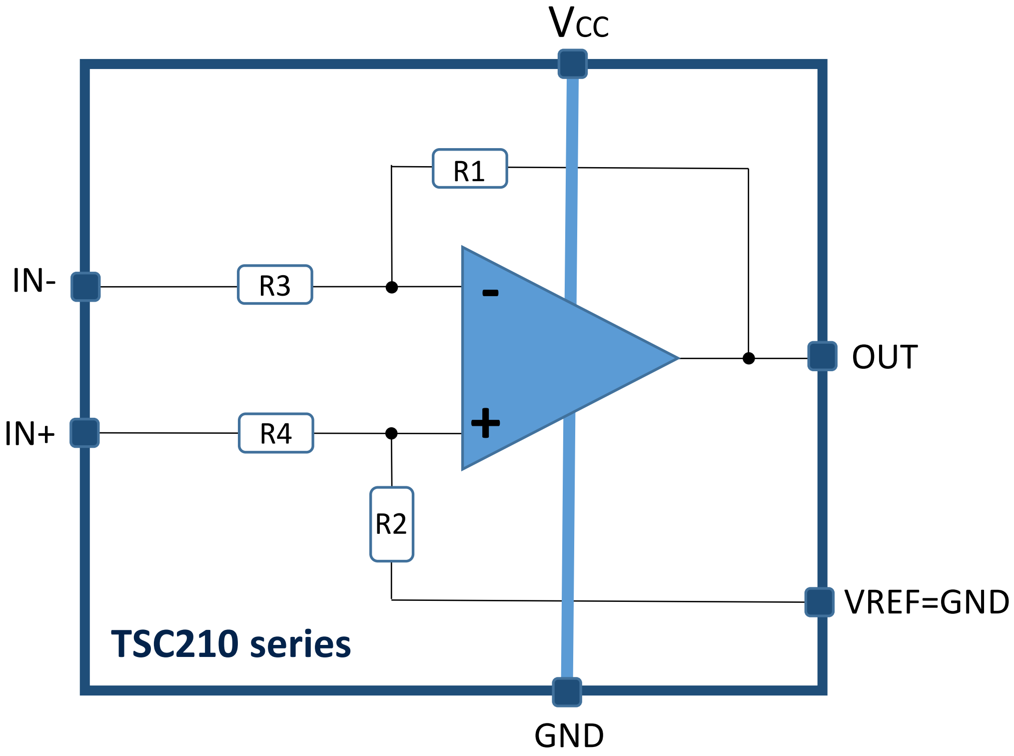
Gain error defines how accurate the current measurement remains across the full dynamic range. Any inaccuracy in current measurement can reduce system efficiency and lead to power losses.

In current sense amplifiers, the gain is generally integrated, which provides better accuracy than solutions using external resistors. However, achieving a perfect match between internal resistors is extremely difficult, so a small gain error always remains and must be included in the current sensing error budget.

1. The ideal transfer function is $y = ax + b$, where b represents the offset and a is the theoretical gain of the current sense amplifier. For the TSC2010, the expected gain is $a = 20$.
2. In practice, resistor matching causes the real transfer function to become $y = cx + b$, where c is the actual gain. For the TSC2010, $c = 20 \pm 0.3\%$.
3. The difference between these two slopes represents the gain error of the current sense amplifier.

Gain error
where does it come from?

Gain resistor mismatch



1

$$out = IN_+ * \frac{R2}{R4} * \frac{1+\frac{R1}{R3}}{1+\frac{R2}{R4}} - IN_- * \frac{R1}{R3}$$

2

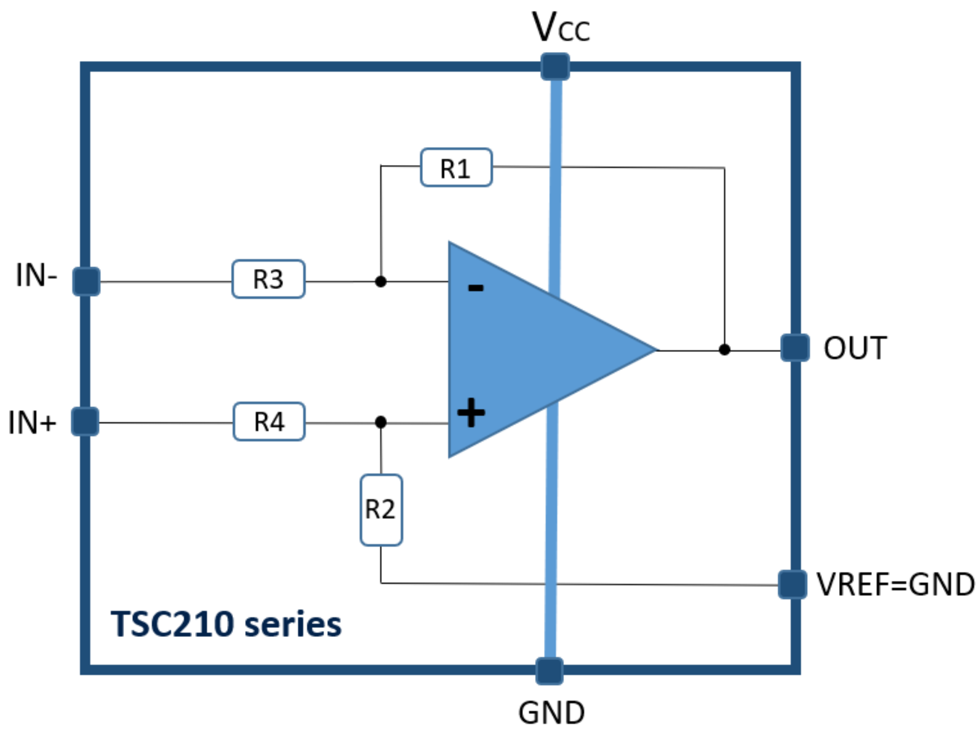
$$out = (IN_+ - IN_-) * \frac{R1}{R3}$$

More than precision, resistors matching is the key for gain accuracy

Explanation

Gain error
where does it come from?

Gain resistor mismatch



$$out = (IN_+ - IN_-) * \boxed{\frac{R1}{R3} * (1 \pm 2\varepsilon)} + \frac{IN_+ + IN_-}{2} * \frac{R1}{R1+R3} * 4\varepsilon$$

Differential gain is given by: $Gain = \frac{R1}{R3}(1 \pm 2\varepsilon)$

4

Where ε represents the resistance acuracy

3

More than precision, resistors matching is the key for gain accuracy

Explanation

Gain error where does it come from?

Explanation of pages 7–9

1. Current-sense amplifiers have an **integrated, predefined gain**. To understand the origin of the **gain error**, we can refer to the traditional differential-amplifier architecture already presented in the **CMRR** study.

2. If we assume that $R1 = R2$ and $R3 = R4$, with perfectly matched resistors, and that $V_{ref} = 0\ V$,the transfer function simplifies to:

$$out = (IN_{+} - IN_{-}) \times \frac{R1}{R3}$$

The differential gain is therefore:

$$Gain = \frac{R1}{R3}$$

3. In practice, perfectly matched resistors can't be achieved in a semiconductor environment. A small mismatch must therefore be considered. This matching error is represented by ε, and including it in the transfer function leads to a more detailed expression.

Gain error
where does it come from?

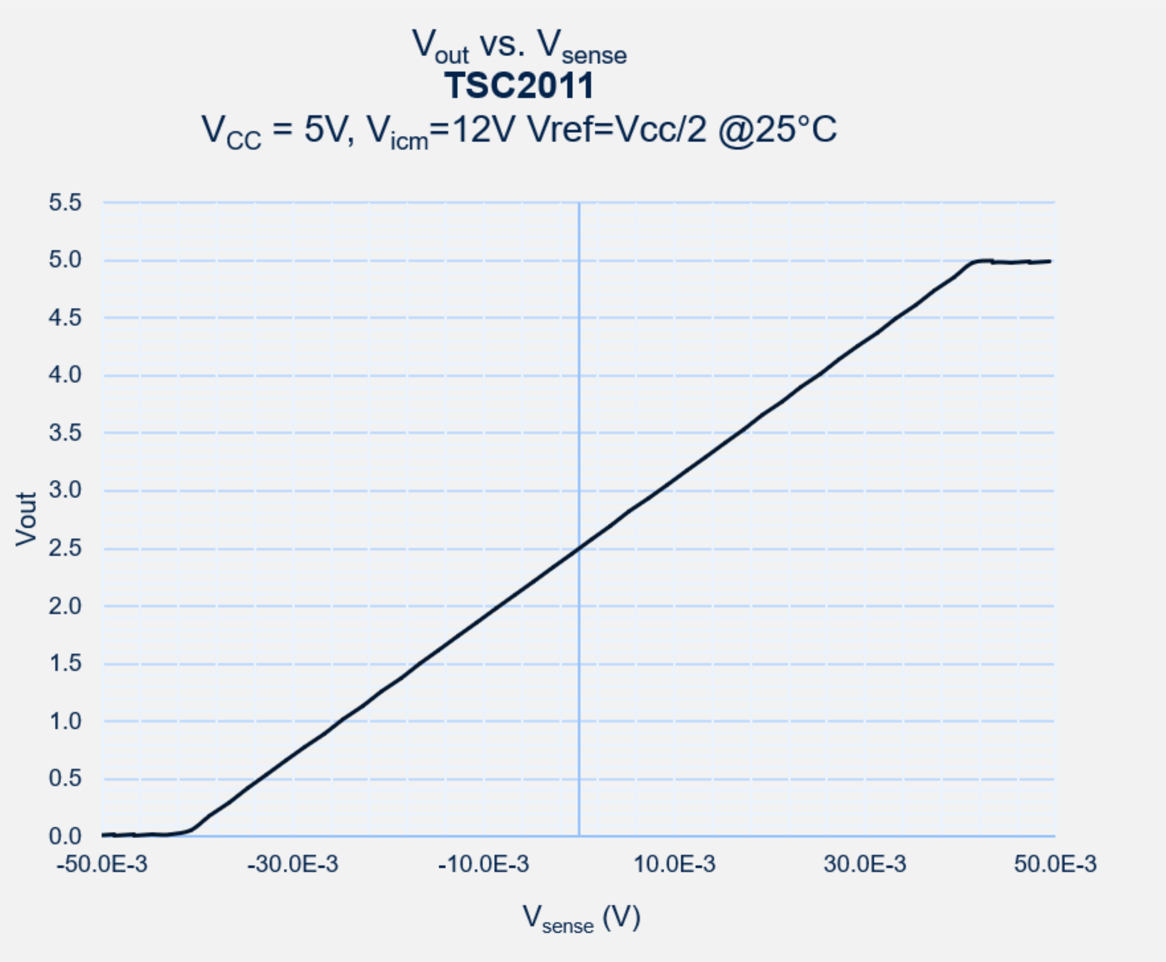
Explanation of pages 7–9

4 In this study we focus only on the gain error, which is given by this term of the equation and all the art of making a precise circuit in terms of the gain error lies in reducing ε as much as possible

This is achieved through the choice of resistor technology, such as **thin-film resistors**, and through careful layout design. More than absolute precision, **resistor matching** is the key factor for gain accuracy.

This is also an advantage of current-sense amplifiers over differential op amp solutions with external gain resistors: they provide very good gain accuracy, while equivalent performance with external resistors would require **expensive components**.

Gain error specification



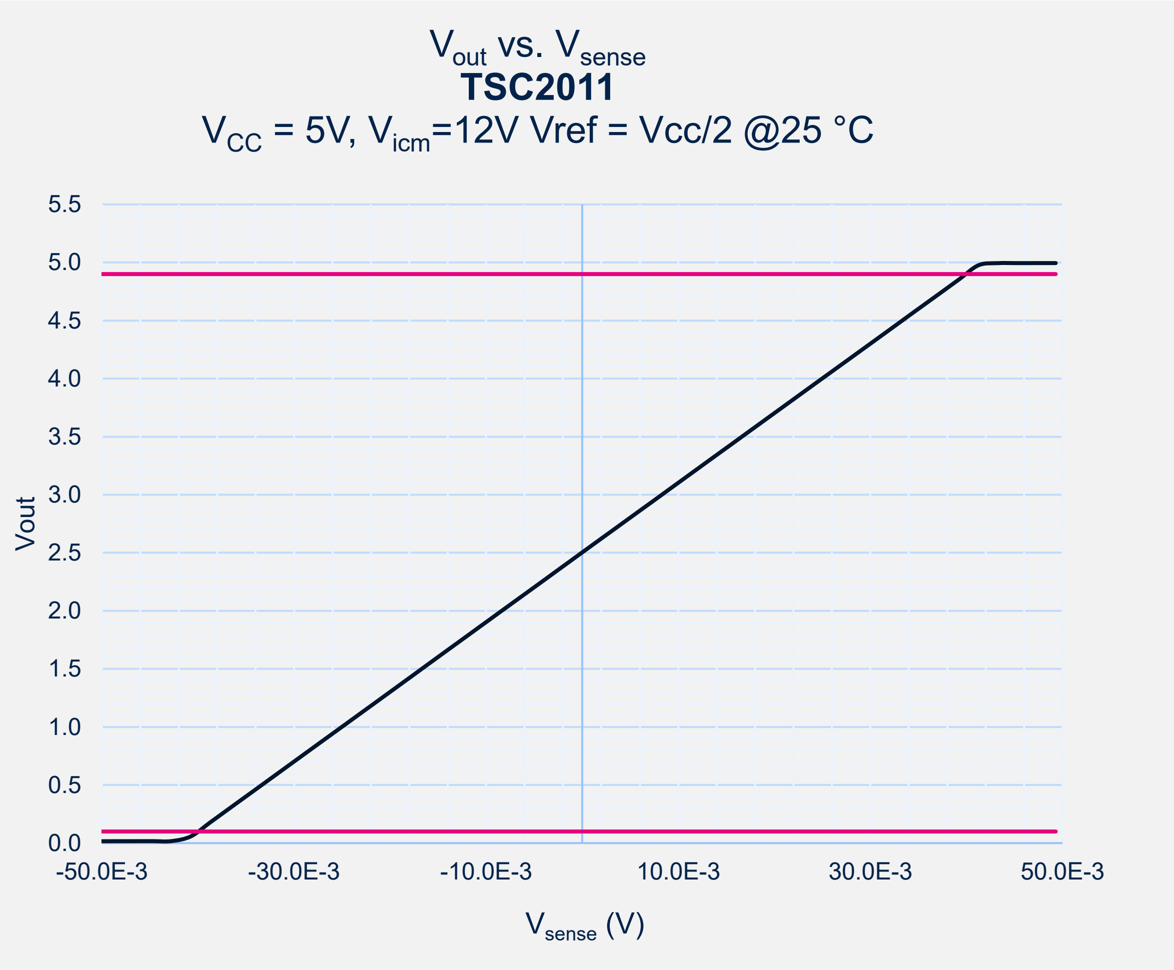
Gain error is guaranteed to max 0.3% for a

- V_{out} from 100 mV to 4.9 V
- V_{sense} =1.7 mV to 81 mV

Output						
G	Gain	TSC2010	20			V/V
		TSC2011	60			
		TSC2012	100			
Eg	Gain error vs. temperature	ΔV_{out} = 100 mV to (V_{cc} - 100 mV)			0.3	%
		$T_{min} < T < T_{max}$			0.3	

Explanation

Gain error specification



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		T_{min} < T < T_{max}		0.3	

Explanation

Gain error specification

Explanation of pages 12–13

For a current-sense amplifier, gain error is **rarely defined over the full input scale**, which can be approximated as:

$$\frac{V_{CC}}{Gain}$$

(page 12) When plotting the output voltage versus the input voltage of a current-sense amplifier, the response shows **saturation limits**, mainly caused by the output transistor limitations.

In addition, as the output approaches saturation, the transfer curve is no longer perfectly linear. As a result, the **gain error increases in this region**.

For this reason, the datasheet specifies the voltage range over which the gain error is guaranteed. Depending on the product, this range may be given either **at the input** or **at the output**.

Gain error specification

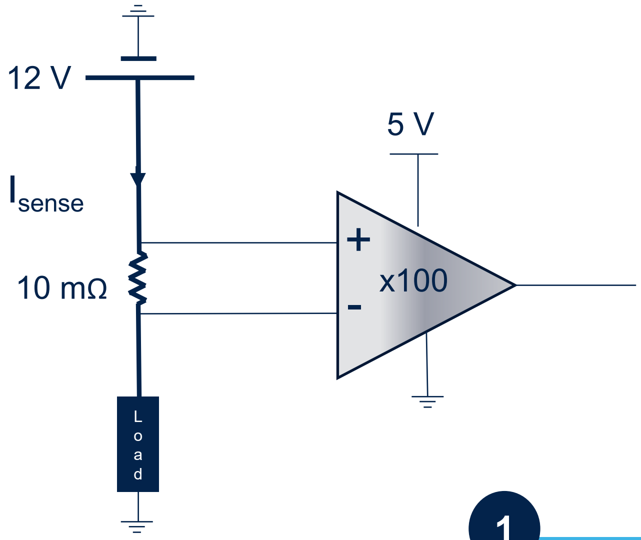
Explanation of pages 12–13

(page 13) In this example, the TSC2011 datasheet guarantees a maximum gain error of **0.3 %** for an output voltage range from **100 mV to 4.9 V** with a supply voltage of $V_{CC} = 5\ V$.

For this device, that corresponds to an input voltage range from **1.7 mV to 81 mV**.

Outside this specified range, a **higher gain error** can be expected.

Example



1

TSC214

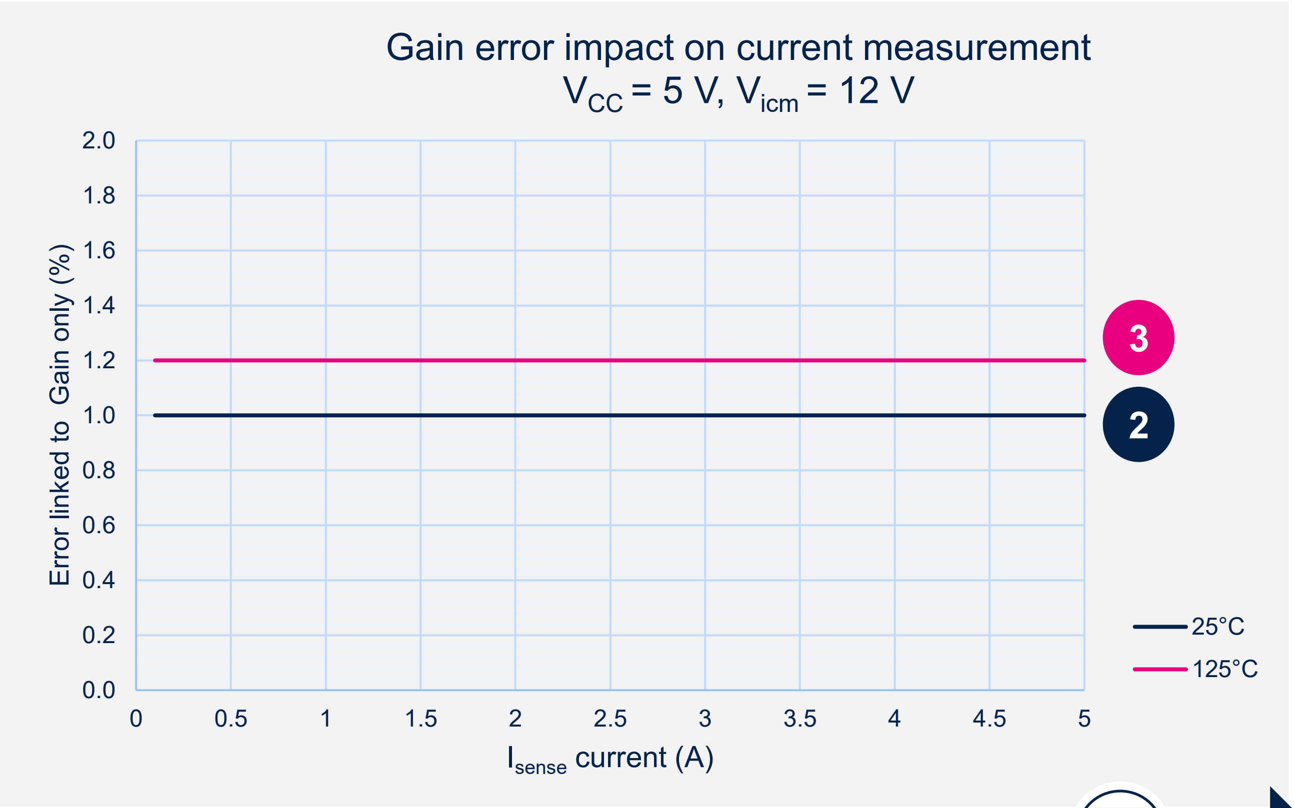
E_G	Gain error	V_{SENSE} = -5 to + 5 mV Tmin. < T < Tmax.	0.02	±1	%
T_G	Gain error vs. temperature	Tmin. < T < Tmax.	7	20	ppm/°C

4

TSC2012

Eg	Gain error vs. temperature	ΔV_{out} = 100 mV to (V_{cc} - 100 mV) $T_{min} < T < T_{max}$	0.3 0.3	%
ΔEg/ΔT	Gain error drift	$T_{min} < T < T_{max}$	25	ppm/°C

$$Gain\ error = Gain.\left(1 + \varepsilon gain + \frac{dG}{dT} * \Delta T\right)$$



Explanation

Explanation of page 16

This example illustrates the impact of **gain error** on current measurement.

1 **Gain error at 25°C**
For the **TSC214**, the datasheet specifies a maximum gain error of **1% at 25°C**, with a gain error drift of **20 ppm/°C**. Using the equation shown, the gain error at **25°C** can therefore be plotted as the **blue curve**.

2 **Error acting as a percentage**
As shown by the blue curve, the gain error is **independent of the current flowing through the shunt**. Its impact is therefore **constant over the entire measured current range**, which is why it is described as an **error acting as a percentage**.

3 **Impact of temperature at 125°C**
If the application temperature rises to **125°C**, the gain error drift of **20 ppm/°C** must be taken into account. Over this temperature range, it represents a gain increase of **0.2%**, which is added to the gain error at **25°C**. The **red curve** therefore shows the maximum gain error that can be expected at **125 °C**.

Example

Explanation of page 16

4 **Specific case of the TSC2012**

In some datasheets, such as for the **TSC2012**, the gain error at **25 °C** is identical to the temperature-gain error, even though a gain drift is also specified. In this case, there's **no direct correlation** between the gain error—mainly linked to resistor matching—and the temperature drift, which is related to another parameter, such as **layout impact**.

For this reason, it's recommended to consider **only the gain error parameter** in the error analysis. In this specific case, the gain drift versus temperature is mainly useful when the application is **calibrated at 25 °C,** for example to estimate the gain error at the target temperature.

Linearity

$$Linearity\ error = \frac{Vout_{\ measured} - Gain(best_{fitline}) * V_{sense} - Offset(best_{fitline})}{Vout_{FullScale}}$$

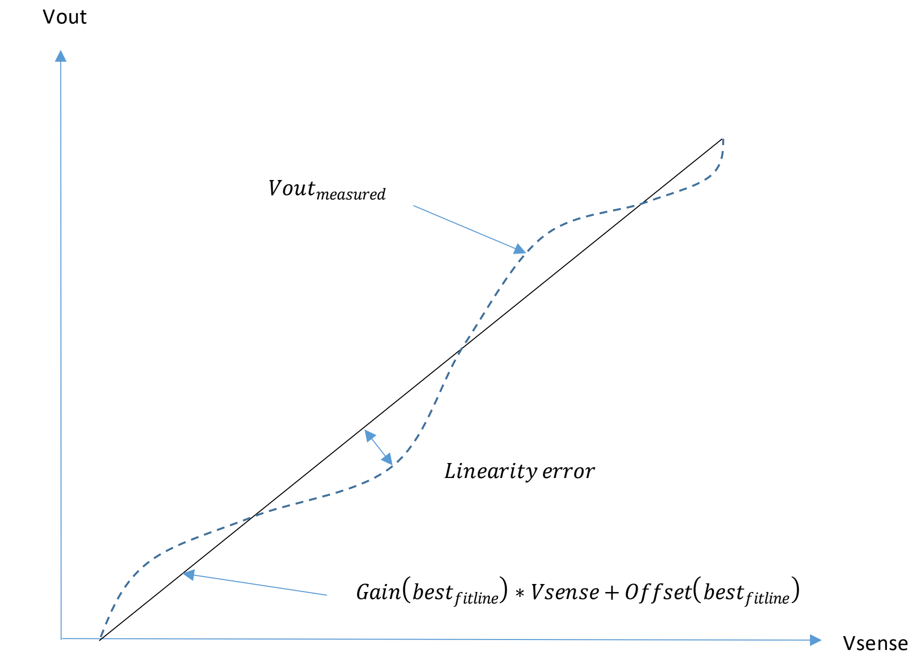
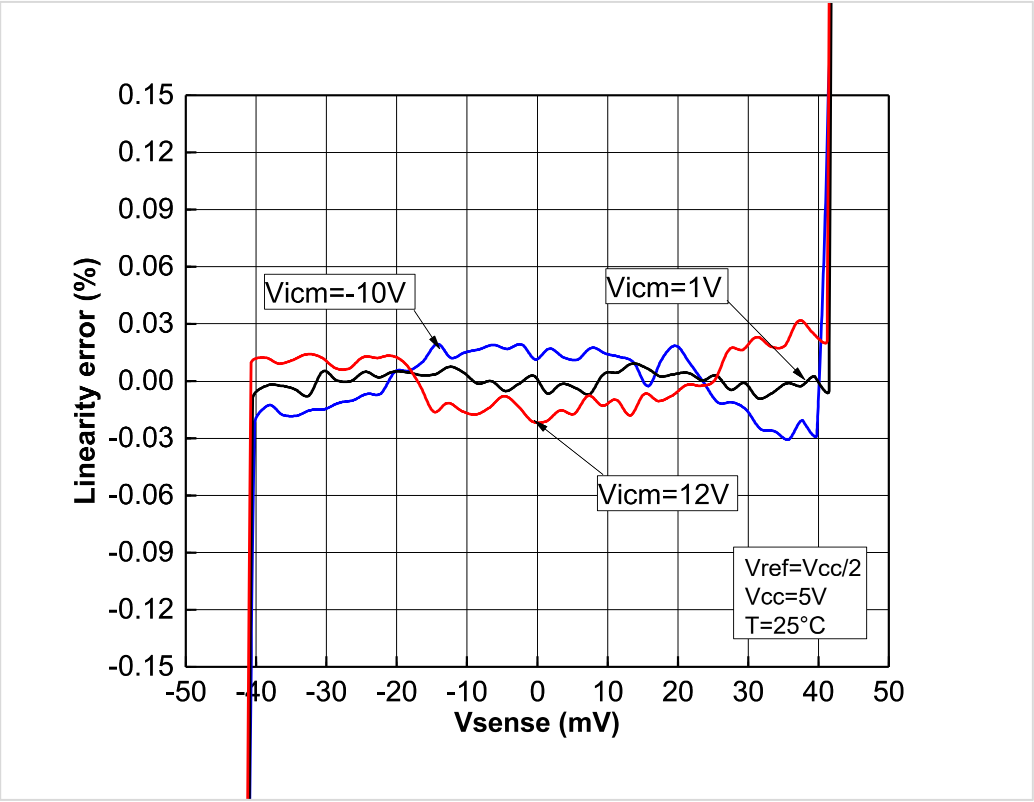


Table 5. Electrical characteristics (V_{CC} = 5 V, V_{icm} = 12 V, T = 25 °C unless otherwise specified)

NLE	Linearity error	V_{icm} = 12 V	0.03		%



Explanation

Explanation of page 19

The **linearity error** indicates whether the gain error specified in the datasheet remains linear over the useful V_{sense} range. Like gain error, it contributes to the total error budget as a **percentage** and isn't directly linked to the current through the shunt resistor.

In practice, gain isn't estimated from only two points, but from a large set of measurement points taken during characterization. Since these points aren't often perfectly aligned, a **best-fit line** is defined. The linearity error is the deviation between the actual measured response and this best-fit line.

This deviation is then referred to the **full-scale output voltage range** to express it as a percentage. In the equation shown, the input-offset voltage is removed to improve accuracy.

In most cases, the linearity error is **much smaller than the gain error** and can be neglected. However, because the gain error is derived from the best-fit line, linearity also indicates whether this gain error stays reasonably constant over the amplifier's linear input range.

It may still be useful to include linearity in the total error budget for specific applications, especially when the gain is **calibrated during production**.

Error acting as a percentage summary

There’s no correlation between these errors and the current to sense

- Gain error
- Linearity

It has the most significant impact for high current

Explanation

Error acting as a percentage summary

Explanation of page 21

This chapter has presented **two error sources** that are **independent of the current range being measured** and whose impact on accuracy acts as a **percentage over the full current range**:

- **Gain error**
- **Linearity**

These errors mainly originate from **internal mismatch**.

Because they act as a percentage, their impact becomes **more significant at high current levels**.

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