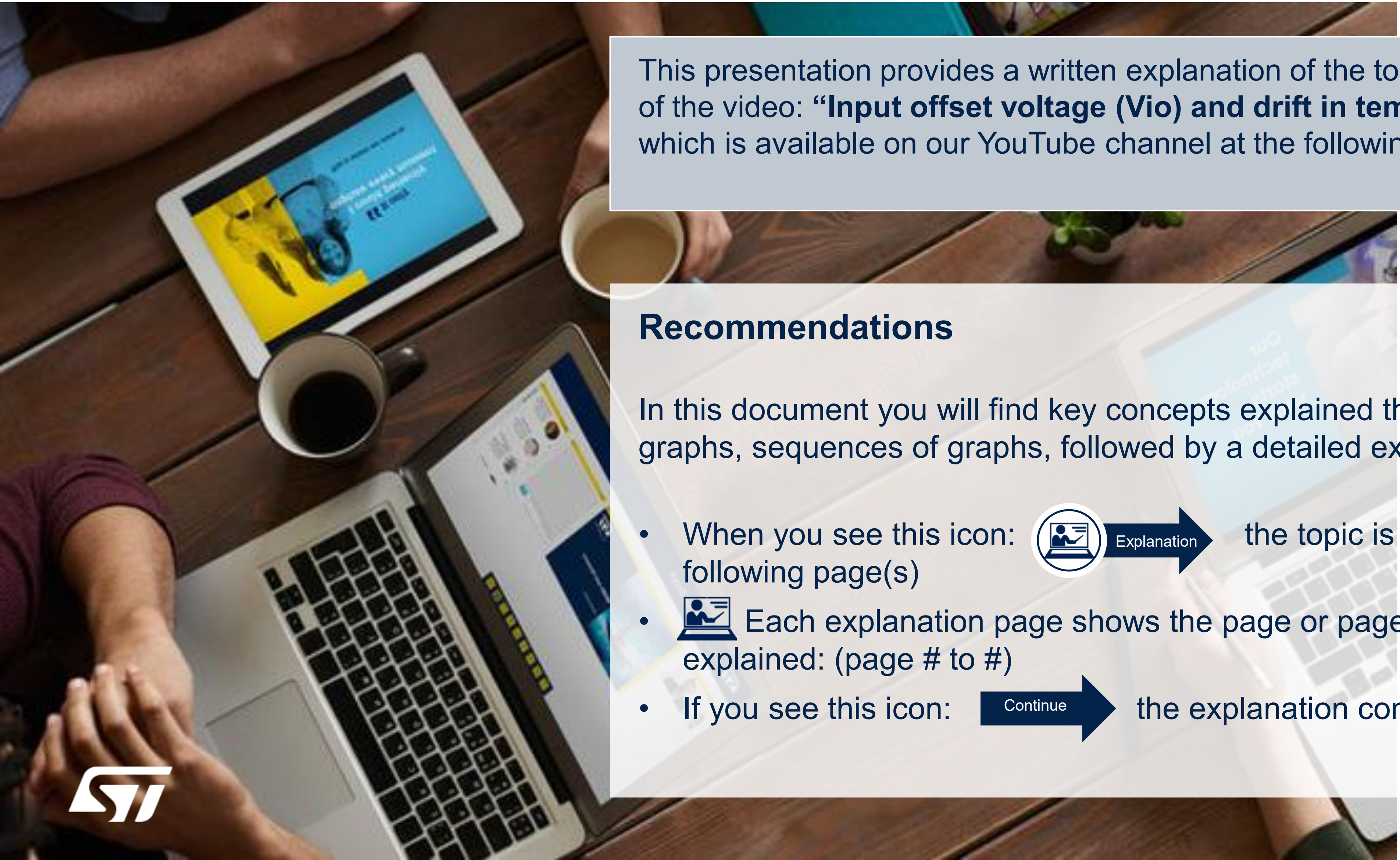
Exploring current sense amplifiers

STMicroelectronics Tech Days

Input offset voltage (V_{io}) and drift in temperature $\left(\frac{\Delta Vio}{\Delta T}\right)$

Chapter 5

User guide



This presentation provides a written explanation of the topic covered in the fifth chapter of the video: **"Input offset voltage (Vio) and drift in temperature ($\Delta Vio/\Delta T$) #5"**, which is available on our YouTube channel at the following link:

Video on YouTube

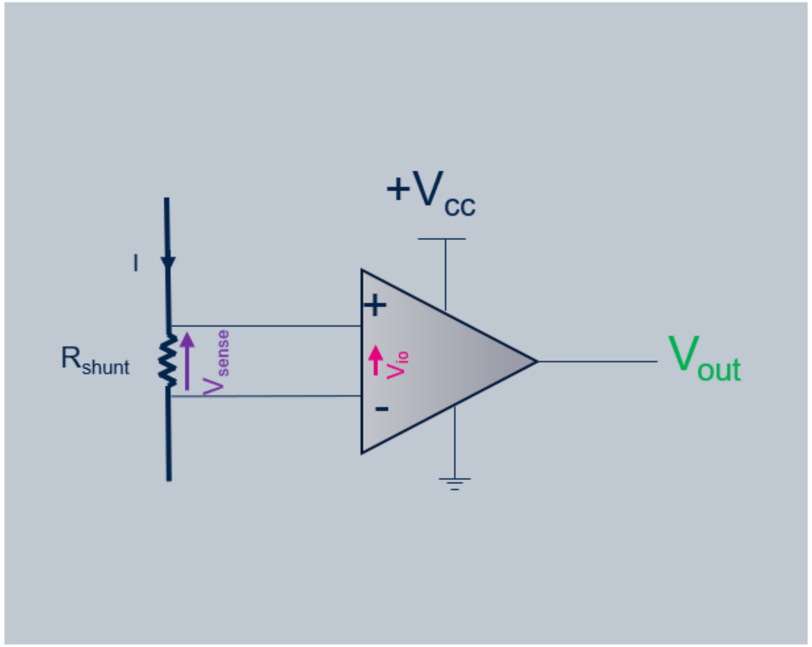
Recommendations

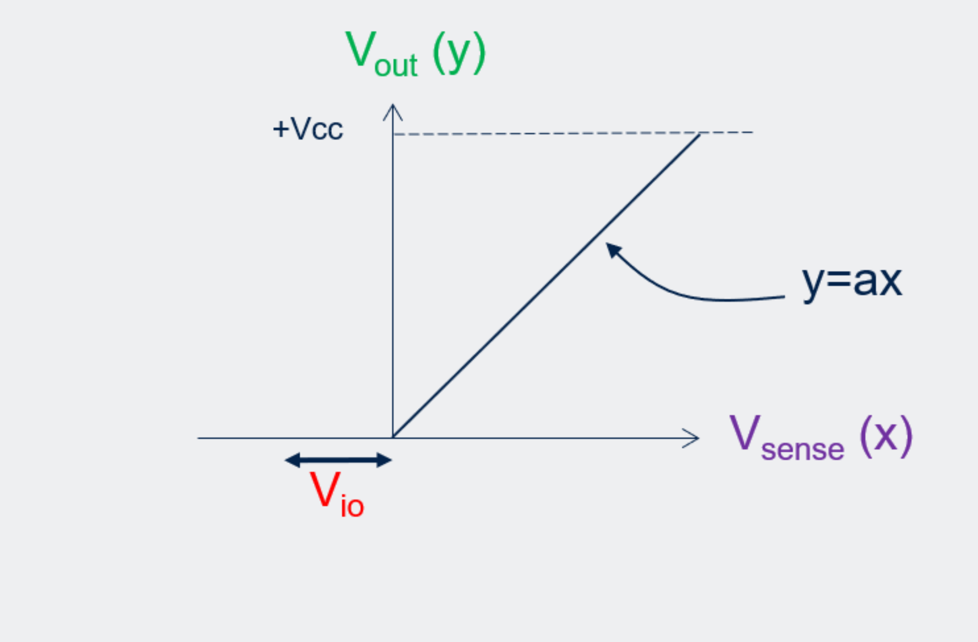
In this document you will find key concepts explained through informative tables, graphs, sequences of graphs, followed by a detailed explanation.

- 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)

What is input offset voltage?

V_{io} offset





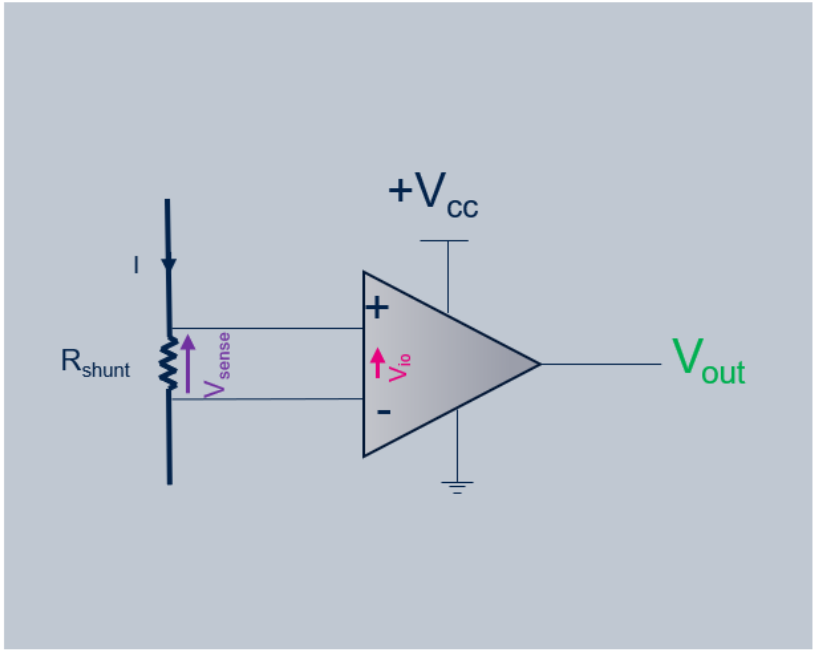
TSC210 series

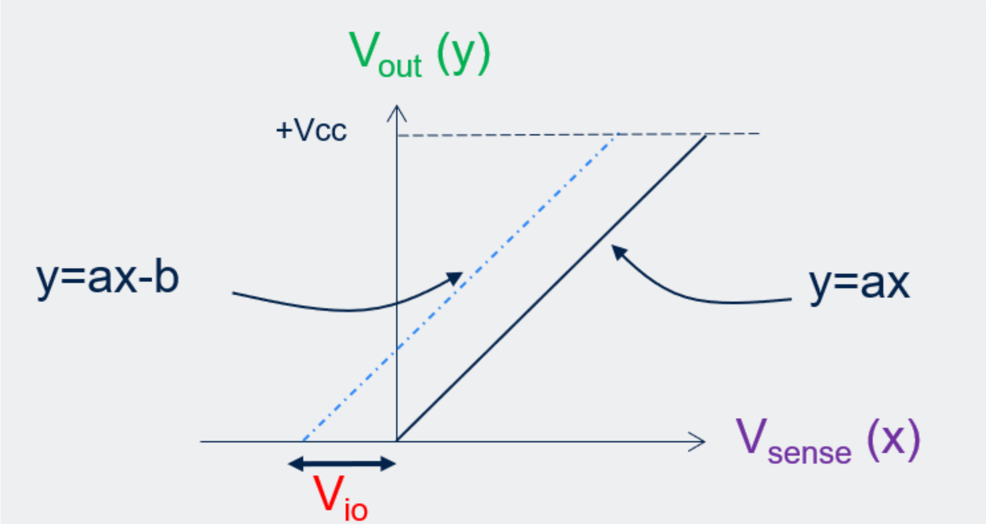
Input						
V_O	Offset voltage (RTI) (1)					
	TSC210, TSC212	V_{SENSE} = 0 mV	-35		35	µV
	TSC213	V_{SENSE} = 0 mV	-100		100	

Explanation

What is input offset voltage?

V_{io} offset





$$V_{io} = -\frac{b}{a}$$

TSC210 series

Input						
V_O	Offset voltage (RTI) [1]					
	TSC210, TSC212	V_{SENSE} = 0 mV	-35		35	µV
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Explanation

What is input offset voltage?

Explanation of pages 4–5

When the differential input voltage of an op amp is zero, the ideal output should also be zero.
In reality, a small differential input voltage is required to force the output to zero.
This voltage is the **input offset voltage**, usually noted **Vio**.

Vio is defined as a DC voltage between the non-inverting and inverting inputs, specified in the electrical characteristics of the datasheet. It can be positive or negative.

(page 4) – Ideal amplifier (no offset)
If the amplifier were ideal, each input voltage level V_{sense} would simply be multiplied by the gain a.
The output voltage would then follow a straight line through the origin:

$$V_{\text{out}} = a \cdot V_{\text{sense}}$$

This is the reference case: pure gain, no error from offset.

Continue

What is input offset voltage?

Explanation of pages 4–5

(page 5) – Real amplifier with offset

In a real amplifier, the input offset voltage adds its “imprint” to the measurement.
The transfer characteristic is shifted, and the output becomes:

$$V_{\mathrm{out}} = a \cdot V_{\mathrm{sense}} - b$$

Referred to the inputs, the offset voltage is:

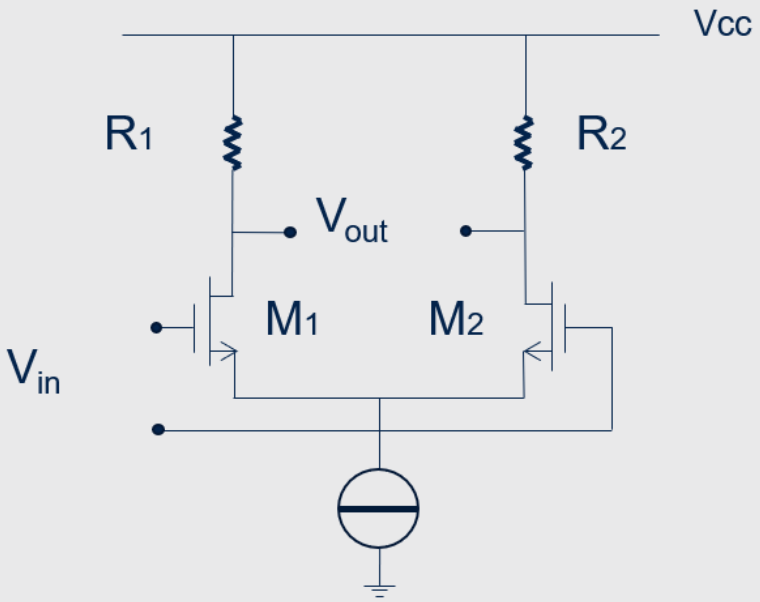
$$V_{\mathrm{io}} = -\frac{b}{a}$$

This input-referred offset causes a first systematic shift and error in the measured current.

The V_{io} value is specific to each amplifier. For accurate current sensing, it is important to choose a device with **low V_{io}**. Chopper-stabilized current-sense amplifiers, such as ST’s [TSC21x] family, exhibit Vio values below **100 µV**, making them particularly suitable for precision DC measurements.

Where does input offset voltage come from?

Differential input



Component mismatch
R1≠R2, M1≠M2 ⇒ offset

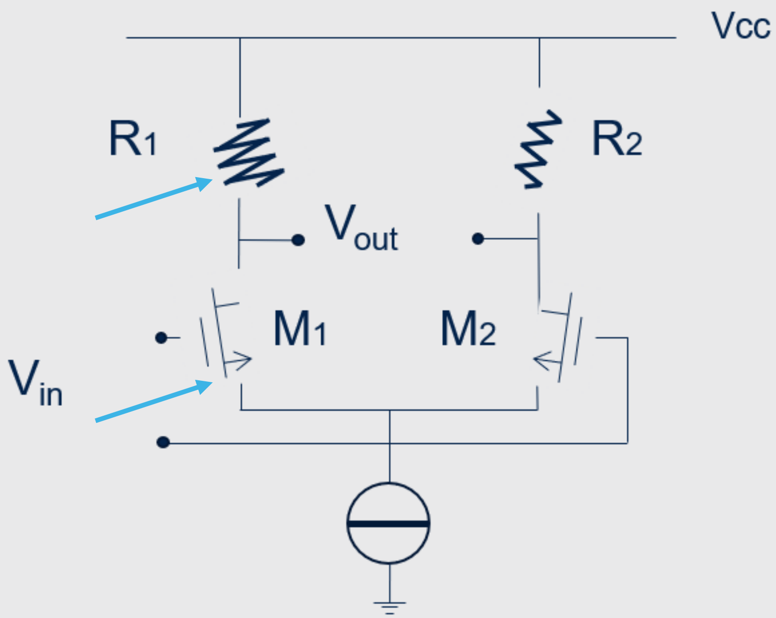
For CMOS technology

Mismatch is mainly due to:
- Doping variations
- Lithographic errors
- Packaging and local stress

Explanation

Where does input offset voltage come from?

Differential input



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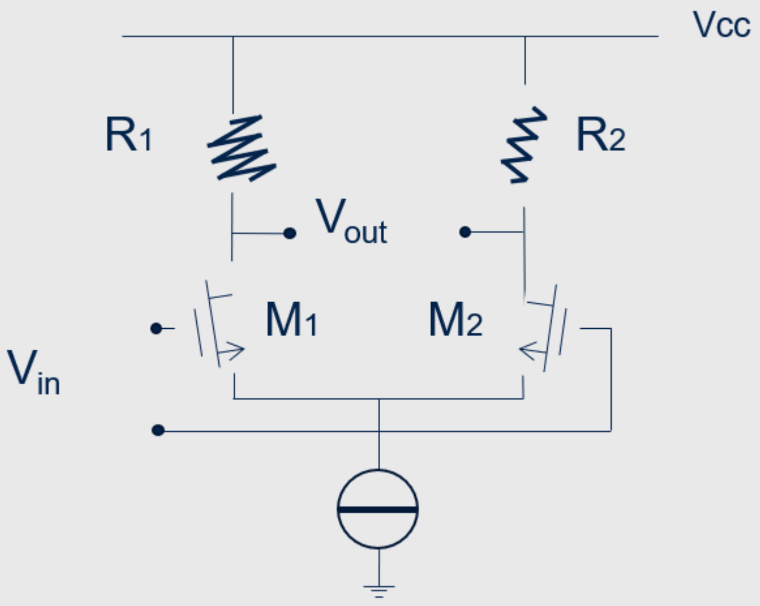
Where does input offset voltage come from?

Differential input



Component mismatch
R1≠R2, M1≠M2 ⇒ offset

For CMOS technology

$$Vos = \Delta Vth + \frac{VGS - VT}{2}\left(\frac{\Delta R}{R} + \frac{\Delta W/L}{W/L}\right)$$

ΔVth linked to the substrate doping
Second term linked to the size of MOS

Mismatch is mainly due to:
- Doping variations
- Lithographic errors
- Packaging and local stress

Explanation

Where does input offset voltage come from?

Explanation of pages 8–10

Where does input offset voltage come from?
The origin of the input offset voltage is well understood.

(page 9) – Mismatch in the differential input stage
In a real differential pair, the two input branches are not perfectly identical.
Small mismatches between components, such as:

- $R_1 \neq R_2$
- $M_1 \neq M_2$

and minor mechanical stress from the package, create a bias imbalance in the input stage.
This imbalance appears as a differential voltage at the amplifier inputs: the input offset voltage.

Continue

Where does input offset voltage come from?

Explanation of pages 8–10

(page 10) – CMOS technology: physical origin

For CMOS input stages, the offset can be expressed by the following relation:

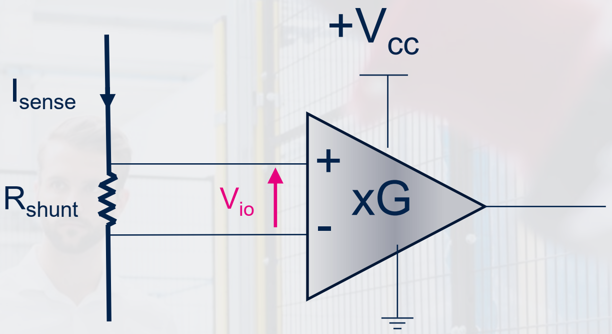
$$V_{\mathrm{OS}} = \Delta V_{\mathrm{th}} + \frac{V_{\mathrm{GS}} - V_{\mathrm{T}}}{2}\left(\frac{\Delta R}{R} + \frac{\Delta W/L}{W/L}\right)$$

- The term ΔV_{th} is linked to substrate doping variations.
- The second term is linked to geometric mismatches: MOS width/length and resistor variations.

The expression contains four contributions. Each can be positive or negative, so they neither all add up nor fully cancel in practice.

Even with careful design and process control, a small residual input offset voltage always remains.

How V_{io} affects precision



$$V_{out} = (Isense * Rshunt + Vio)xG$$

$$V_{io}\ impact\ (\%) = \frac{\pm Vio}{R_{shunt} * Isense} * 100$$

Note: the input-offset voltage has the most significant impact when measuring low current

Explanation

How V_{io} affects precision

Explanation of page 13

In a shunt-based current-sensing application, the measurement relies on Ohm's law: the ideal sense voltage is:

$$V_{\text{sense}} = R_{\text{shunt}} \cdot I_{\text{sense}}.$$

In practice, the amplifier's input offset voltage V_{io} must be added in the output equation:

$$V_{\text{out}} = (I_{\text{sense}} \cdot R_{\text{shunt}} \pm V_{\text{io}}) \cdot G$$

From this, the relative error due to V_{io} is:

$$V_{\text{io impact}}(\%) = \frac{\pm V_{\text{io}}}{R_{\text{shunt}} \cdot I_{\text{sense}}} \cdot 100$$

This shows that the offset error becomes dominant at low currents where $R_{\text{shunt}} \cdot I_{\text{sense}}$ is small.

Continue

How V_{io} affects precision

Explanation of page 13

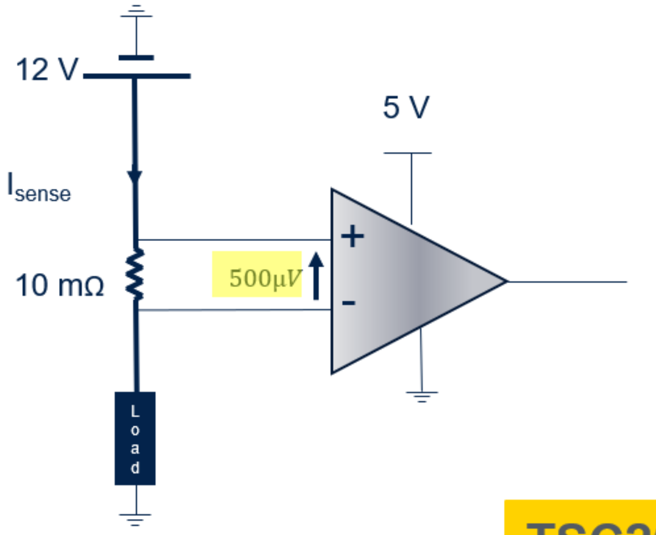
There are two ways to reduce this error:

Increase R_{shunt} to raise V_{sense} ,at the cost of higher power dissipation.

Use a current-sense amplifier with low input offset voltage, such as the **TSC21x** family, which allows smaller, more cost-effective shunts and improves overall system efficiency.

Note: Input offset voltage has the strongest impact when measuring low currents.

Example

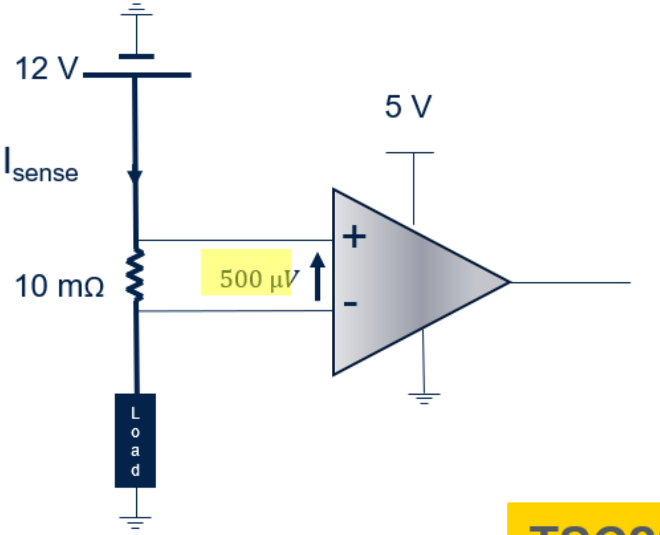


TSC2012

$\|V_{os}\|$	Offset voltage (RTI) (1)	V_{icm} = 1 V			200	µV
		$T_{min} < T < T_{max}$			700	
		V_{icm} = 12 V			500	
		$T_{min} < T < T_{max}$			1100	

Explanation

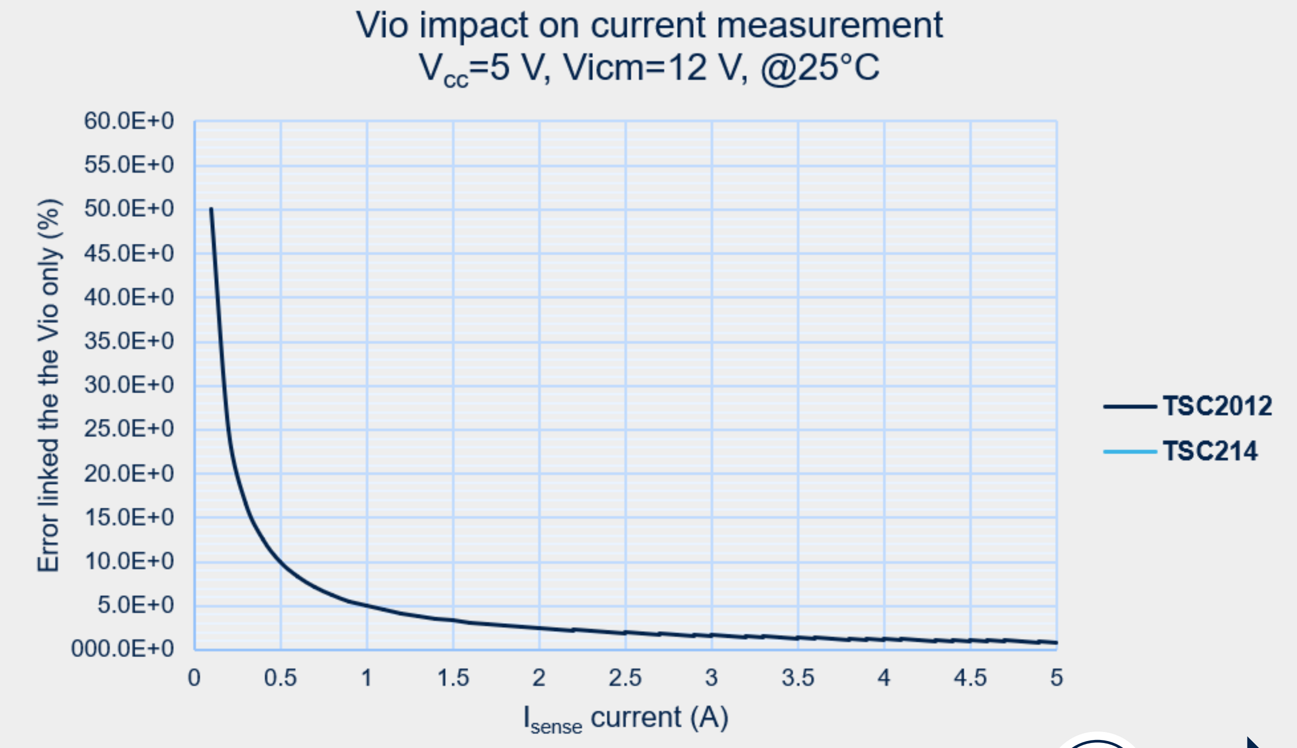
Example



TSC2012

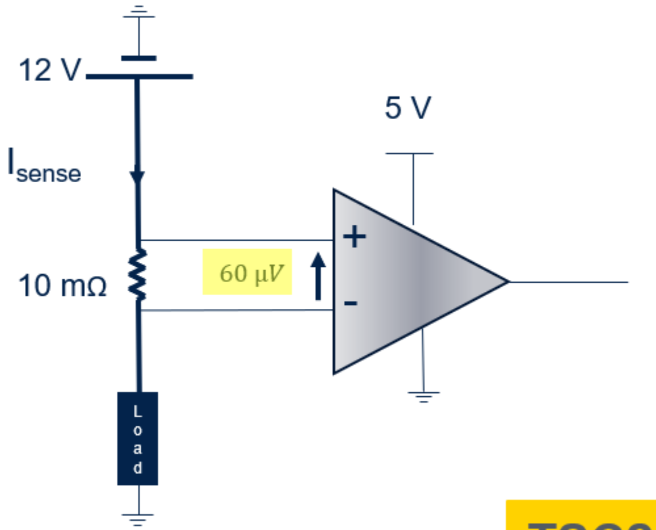
$\lvert V_{os} \rvert$	Offset voltage (RTI) (1)	V_{icm} = 1 V			200	µV
		$T_{min} < T < T_{max}$			700	
		V_{icm} = 12 V			500	
		$T_{min} < T < T_{max}$			1100	

$$V_{io}\ impact\ (\%) = \frac{0.5\ mV}{10\ \text{m}\Omega * I_{sense}} * 100$$



Explanation

Example



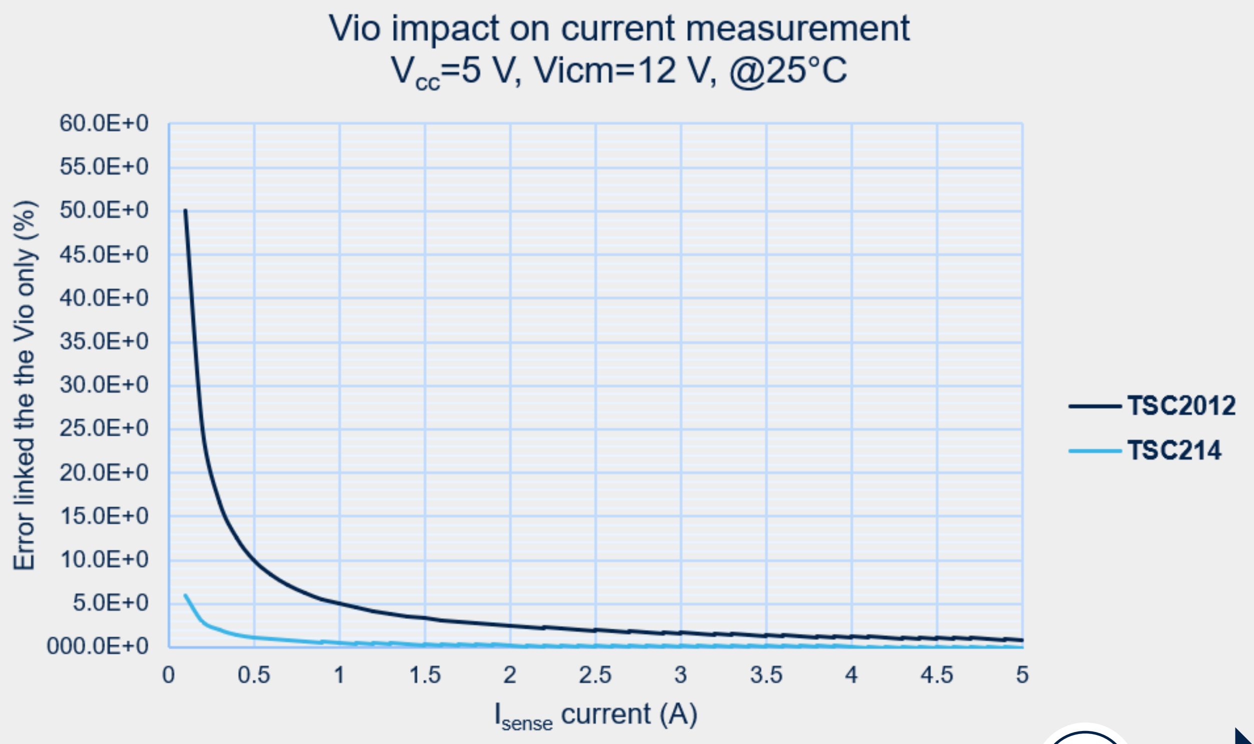
TSC2012

$\lvert V_{os} \rvert$	Offset voltage (RTI) (1)	V_{icm} = 1 V			200	µV
		$T_{min} < T < T_{max}$			700	µV
		V_{icm} = 12 V			500	µV
		$T_{min} < T < T_{max}$			1100	µV

TSC214

V_O	Offset voltage (RTI) (1)					
	TSC210, TSC211, TSC212	V_{SENSE} = 0 mV	-35		35	µV
	TSC214, TSC215	V_{SENSE} = 0 mV	-60		60	µV
	TSC213	V_{SENSE} = 0 mV	-100		100	µV

$$V_{io}\ impact\ (\%) = \frac{60\ \mu V}{10\ m\Omega * I_{sense}} * 100$$



Explanation

Explanation of pages 16–18

To illustrate the impact of V_{io} on current measurement, consider a simple 12 V application.
We measure the load current in a high-side configuration using a $10\ \mathrm{m\Omega}$ shunt, over a range from $100\ \mathrm{mA}$ to $5\ \mathrm{A}$.

(page 16) – Using TSC2012
We first select the TSC2012 current-sense amplifier with a gain of 100.
At $25°\mathrm{C}$, its maximum input offset voltage V_{io} is $500\ \mu V$.

(page 17) – Error due to V_{io}
The relative error linked to V_{io} can be expressed as:

$$V_{\mathrm{io\ impact}}(\%) = \frac{\pm V_{\mathrm{io}}}{10\ \mathrm{m\Omega} \cdot I_{\mathrm{sense}}} \cdot 100$$

When we plot this error versus the current through the shunt, we see that for currents below $1\ \mathrm{A}$, the measurement error becomes significant.
As I_{sense} increases, the error rapidly decreases and falls below 5% once the current exceeds approximately $1\ \mathrm{A}$.

Continue

Explanation of pages 16–18

(page 18) – Using TSC214 to improve accuracy

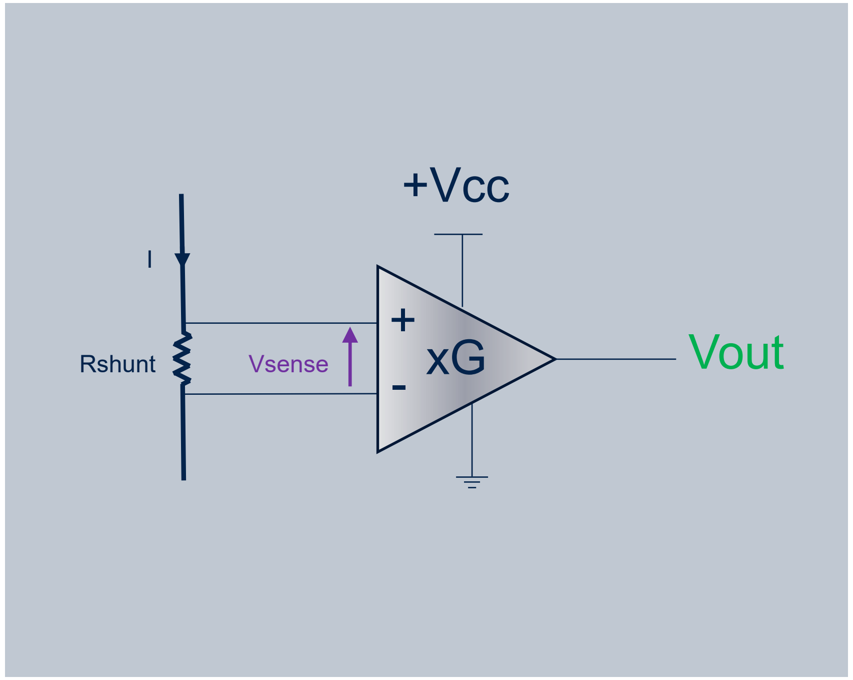
To improve accuracy, we now choose the **TSC214,** also with a gain of 100, but with a much lower V_{io} : only $60\ \mu\mathrm{V}$ maximum at $25°\mathrm{C}$, almost ten times smaller.

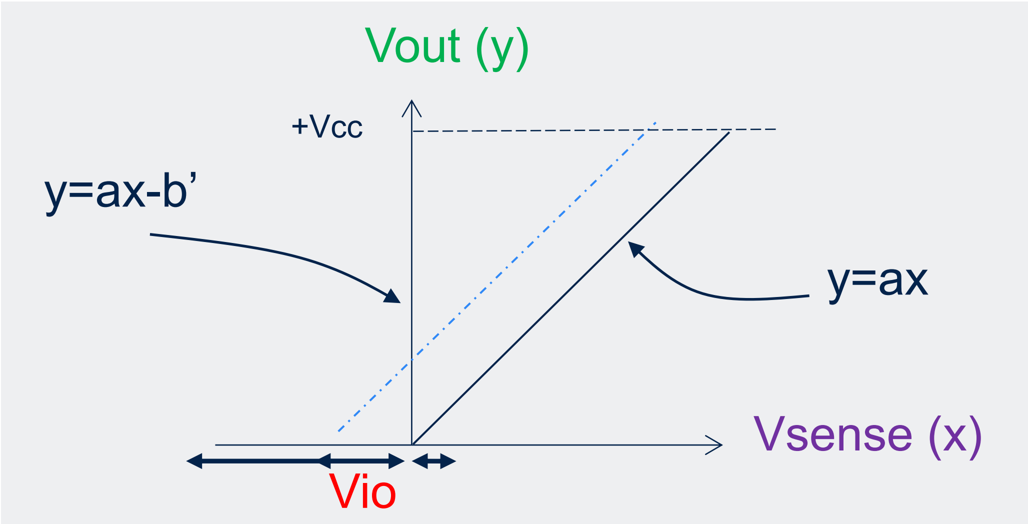
On the updated graph, we immediately observe the improvement: with the **TSC214**, the current-measurement error remains below 5% over nearly the entire $100\ \mathrm{mA}–5\ \mathrm{A}$ range.

This example shows that input offset voltage V_{io} is a key parameter when accurate current measurement is required.

Is input offset voltage stable with temperature?

Offset drift vs temperature





$$Vio = \frac{-b'}{a}$$

TSC21x family

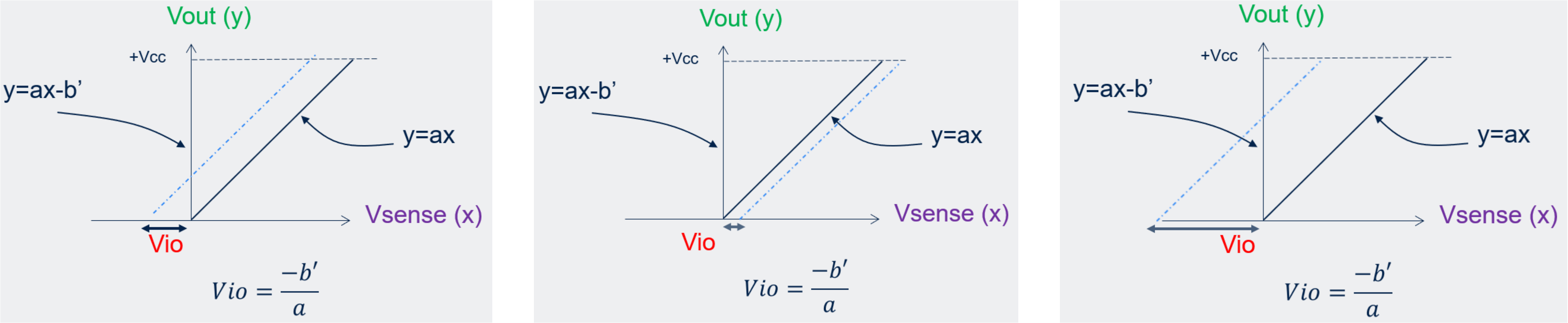
$\lvert \Delta V_O/\Delta_T \rvert$	Offset voltage variation (RTI) vs. temperature	V_{SENSE} = 0 mV, Tmin.< T < Tmax.		0.05	0.3	µV/°C

$$\frac{\Delta Vio}{\Delta T} = \max\left|\frac{Vio(T) - Vio(25°C)}{T - 25°C}\right|$$

Explanation

Is input offset voltage stable with temperature?

Offset drift vs. temperature



(Animation 1) **(Animation 2)**

TSC21x family

$\lvert\Delta V_O/\Delta_T\rvert$	Offset voltage variation (RTI) vs. temperature	V_{SENSE} = 0 mV, Tmin.< T < Tmax.		0.05	0.3	µV/°C

$$\frac{\Delta Vio}{\Delta T} = \max\left|\frac{Vio(T) - Vio(25°C)}{T - 25°C}\right|$$

Explanation

Is input offset voltage stable with temperature?

Explanation of pages 21–22

Input offset voltage V_{io} mainly comes from mismatches in the input components of the amplifier.

Animation 1 – Temperature dependence

Because of these mismatches, V_{io} also varies with ambient temperature.
In precision applications, it is therefore essential to consider the offset drift with temperature, usually denoted $\Delta V_{\text{io}}/\Delta T$ and expressed in $\mathrm{V}/°\mathrm{C}$.

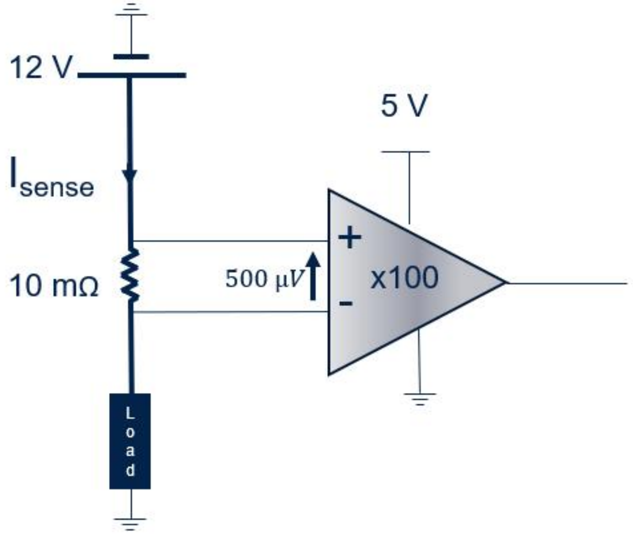
Animation 2 – Drift referenced to $25°\mathrm{C}$

This temperature coefficient is typically referenced to $25°\mathrm{C}$.
For any temperature T above or below $25°\mathrm{C}$, the effective drift is obtained from:

$$\frac{\Delta V_{\text{io}}}{\Delta T} = \max\left|\frac{V_{\text{io}}(T) - V_{\text{io}}(25°\mathrm{C})}{T - 25°\mathrm{C}}\right|$$

This additional term must be included when calculating the total current-measurement error over temperature.

Example



TSC2012

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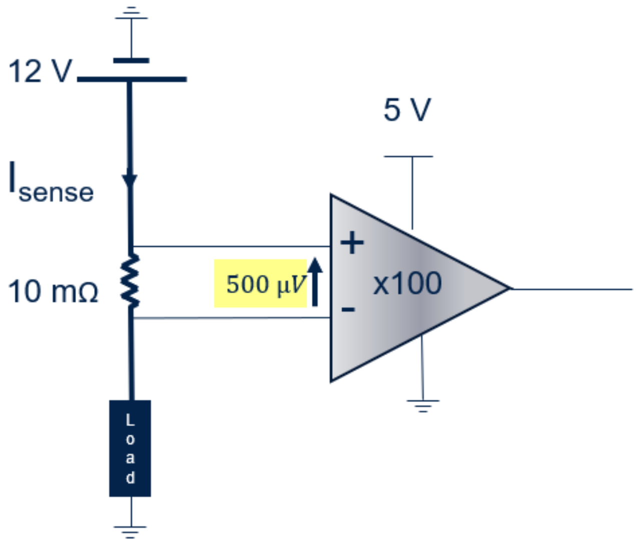
		$T_{min} < T < T_{max}$	700	
		V_{icm} = 12 V	500	
		$T_{min} < T < T_{max}$	1100	

$$V_{io}\ impact\ (\%) = \frac{\pm Vio \pm \frac{\Delta vio}{\Delta T} * \Delta T}{R_{shunt} * I_{sense}} * 100$$

Explanation

Example



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$\lvert V_{os} \rvert$	Offset voltage (RTI) [(1)]	V_{icm} = 1 V	200	µV
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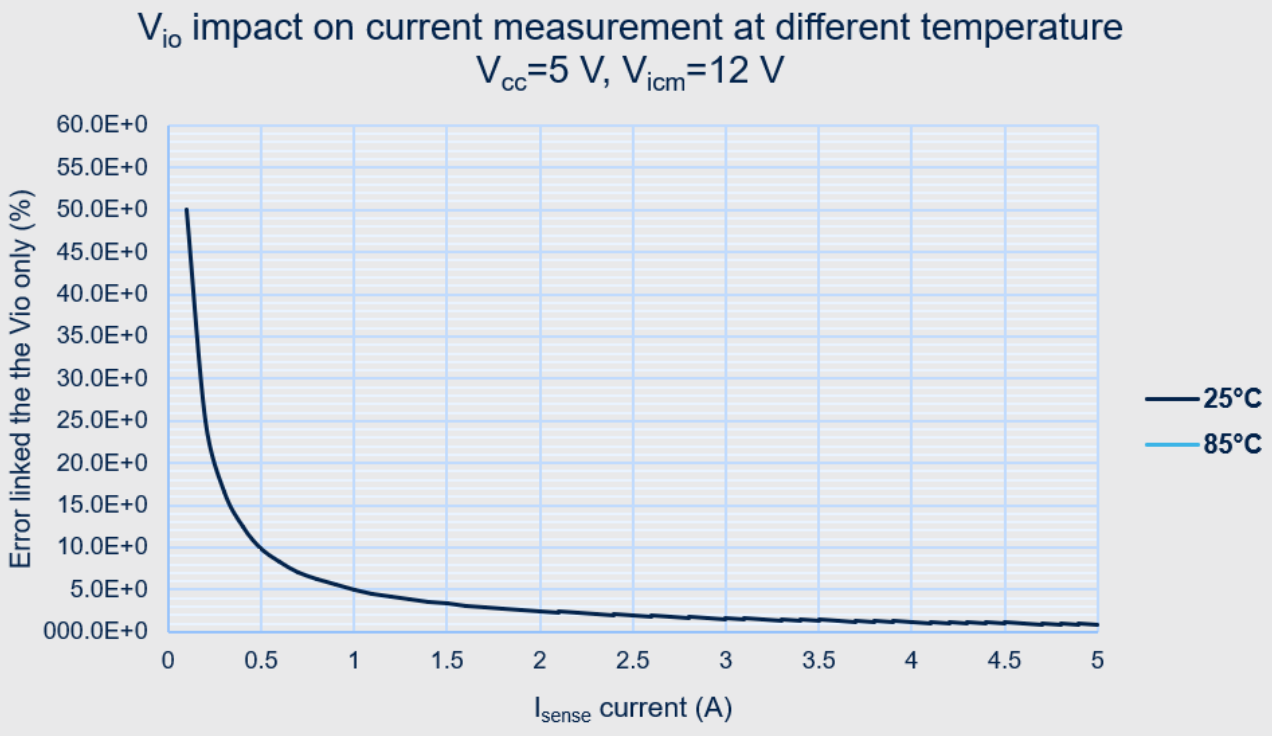
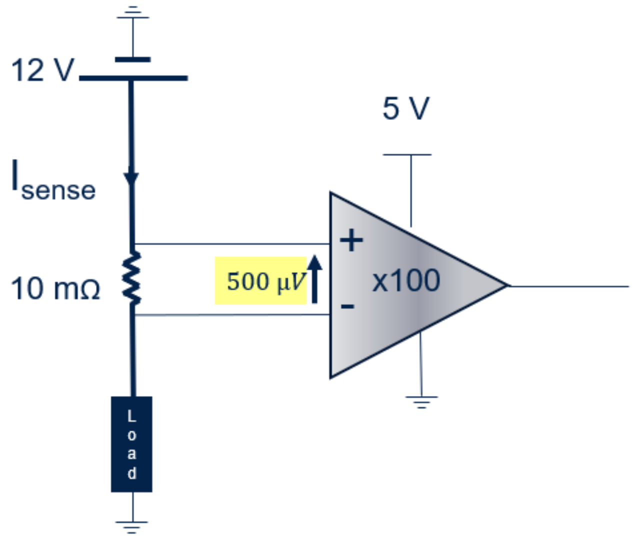
		$T_{min} < T < T_{max}$	1100	

$$V_{io}\ impact\ (\%) = \frac{\pm Vio \pm \frac{\Delta vio}{\Delta T} * \Delta T}{R_{shunt} * I_{sense}} * 100$$



Explanation

Example

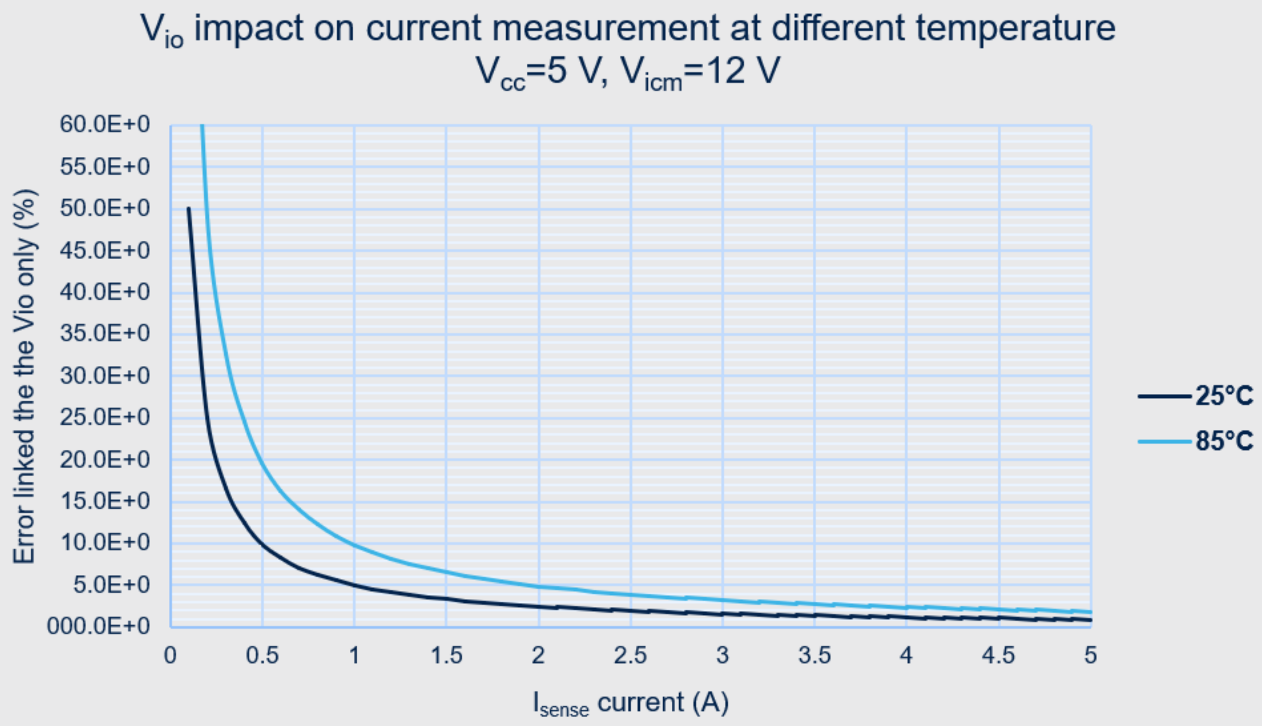


TSC2012

$\lvert V_{os} \rvert$	Offset voltage (RTI) (1)	V_{icm} = 1 V $T_{min} < T < T_{max}$	200 700	µV
		V_{icm} = 12 V $T_{min} < T < T_{max}$	500 1100	

$\lvert \Delta V_{os}/\Delta T \rvert$	Offset drift vs. temperature	V_{icm} = 1 V, $T_{min} < T < T_{max}$	5	µV/°C
		V_{icm} = 12 V, $T_{min} < T < T_{max}$	8	

$$V_{io}\ impact\ (\%) = \frac{\pm Vio \pm \frac{\Delta vio}{\Delta T} * \Delta T}{R_{shunt} * I_{sense}} * 100$$



Explanation

Explanation of pages 24–26

(page 24) We reuse the same TSC2012 example, but this time we focus on its behavior versus temperature.
To do this, we extend the previous error equation by adding the temperature-drift term $\Delta V_{io}/\Delta T$.

(page 25) – Reference at 25 °C
At $25°\mathrm{C}$, the drift term is zero, so it does not affect the measurement.
The resulting error curve is therefore identical to the one we obtained previously.

(page 26) – Case at 85 °C
If the temperature increases to $85°\mathrm{C}$, the offset grows by:

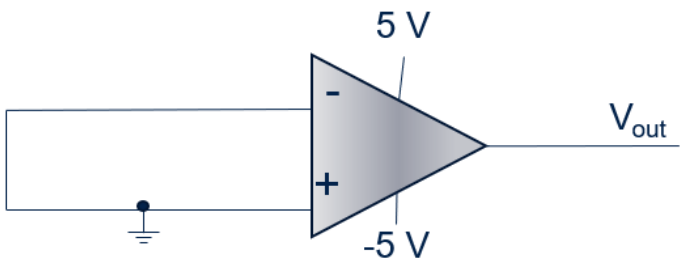
$$8\ \mu\mathrm{V}/°\mathrm{C} \times 60°\mathrm{C} = 480\ \mu\mathrm{V}$$

The effective offset at $85°\mathrm{C}$ becomes:

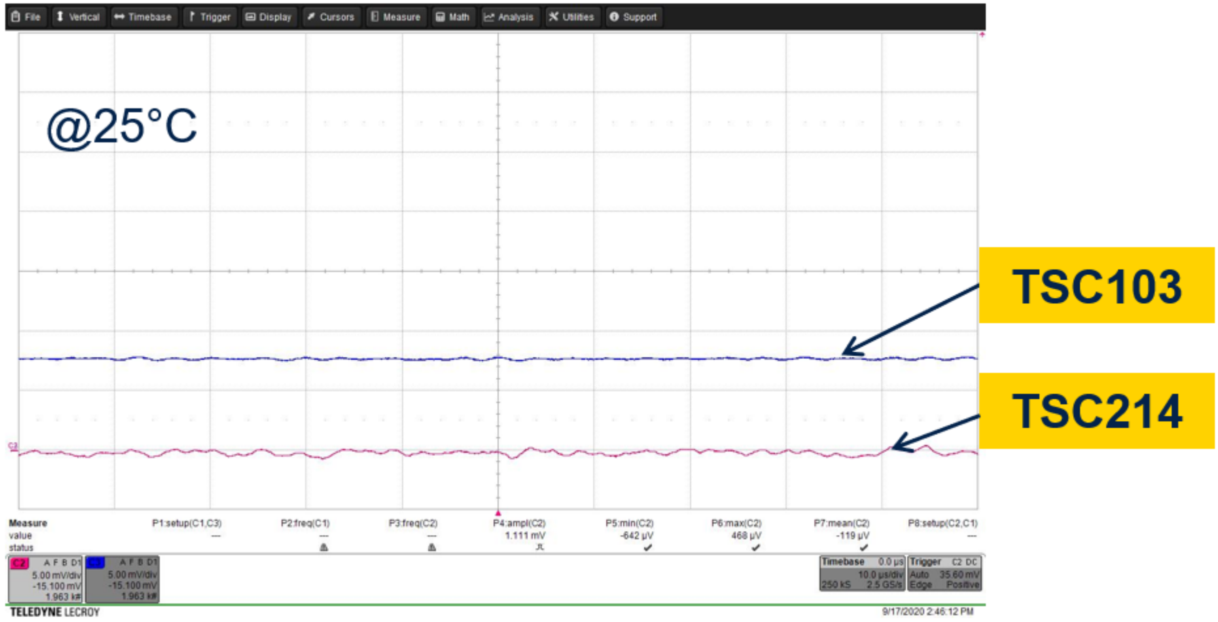
$$500\ \mu\mathrm{V} + 480\ \mu\mathrm{V} = 980\ \mu\mathrm{V}$$

This value must be used in the error calculation.
From the plotted curve, we can see that, at $85°\mathrm{C}$, the **TSC2012** keeps the measurement error below 5% only for currents above about $2\ \mathrm{A}$.

$\Delta V_{io}/\Delta T$ and calibration



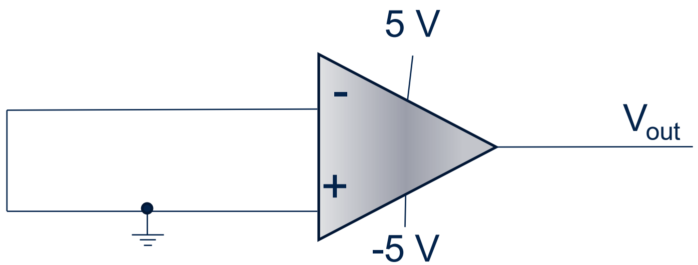
$V_{out} = \pm V_{io} * 100$



	V_{io} @25°C max	Δvio/Δt max
TSC214	60 µV	300 nV/°C
TSC103	1.5 mV	5 µV/°C

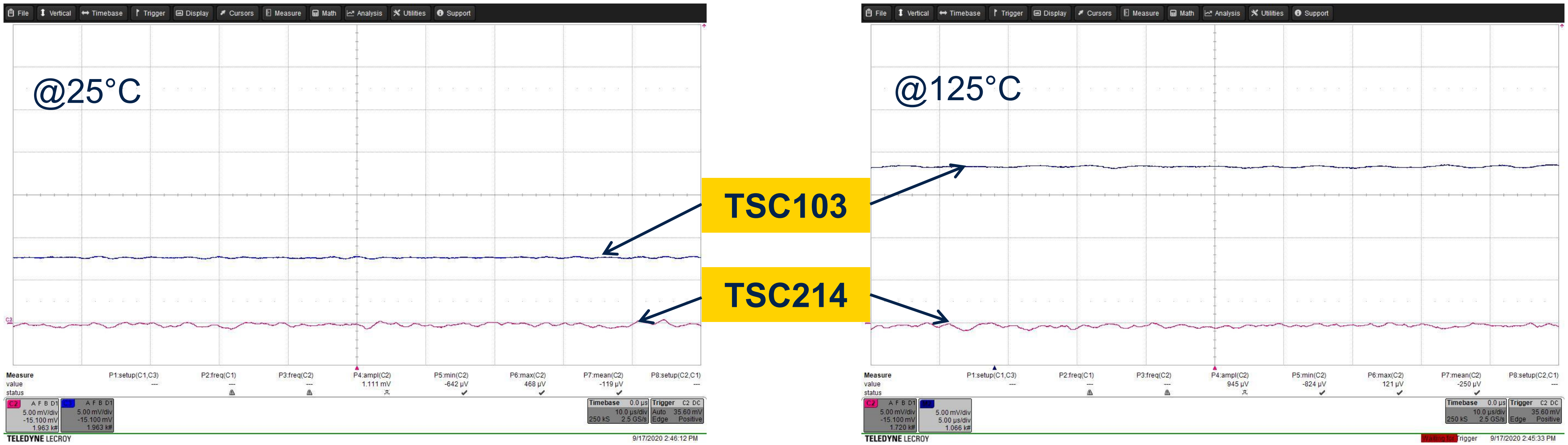
Explanation

$\Delta V_{io}/\Delta T$ and calibration



$V_{out} = \pm V_{io} * 100$

$V_{out} = V_{io} \pm dT\left(\frac{\Delta V_{io}}{\Delta T}\right) * 100$



	V_{io} @25°C max	Δvio/Δt max
TSC214	60 µV	300 nV/°C
TSC103	1.5 mV	5 µV/°C

Explanation

$\Delta V_{io}/\Delta T$ and calibration

Explanation of pages 28–29

When analyzing the error due to input offset voltage, it is essential to consider its temperature drift at the same time. While the input offset voltage V_{io} can be calibrated out at production, compensating for offset drift over temperature is much more difficult.

(page 28) – Comparison at 25 °C
We compare two current-sensing amplifiers with different V_{io} and $\Delta V_{io}/\Delta T$ characteristics:

- TSC214: $V_{io} = 60\ \mu\text{V}$, $\Delta V_{io}/\Delta T = 0.3\ \mu\text{V}/°\text{C}$
- TSC103: $V_{io} = 1500\ \mu\text{V}$, $\Delta V_{io}/\Delta T = 5\ \mu\text{V}/°\text{C}$ lower-precision device

Both devices have a gain of 100, so:

$$V_{out} = \pm V_{io} \times 100$$

On the oscilloscope at $25°\text{C}$, the **TSC103** shows an output offset of about $8\ \text{mV}$, whereas the **TSC214** output is close to $0\ \text{V}$. This means that if the **TSC103** is used in an accurate application, a production-time calibration is required to remove this offset.

$\Delta V_{io}/\Delta T$ and calibration

Explanations of pages 28–29

(page 29) – Behavior with temperature

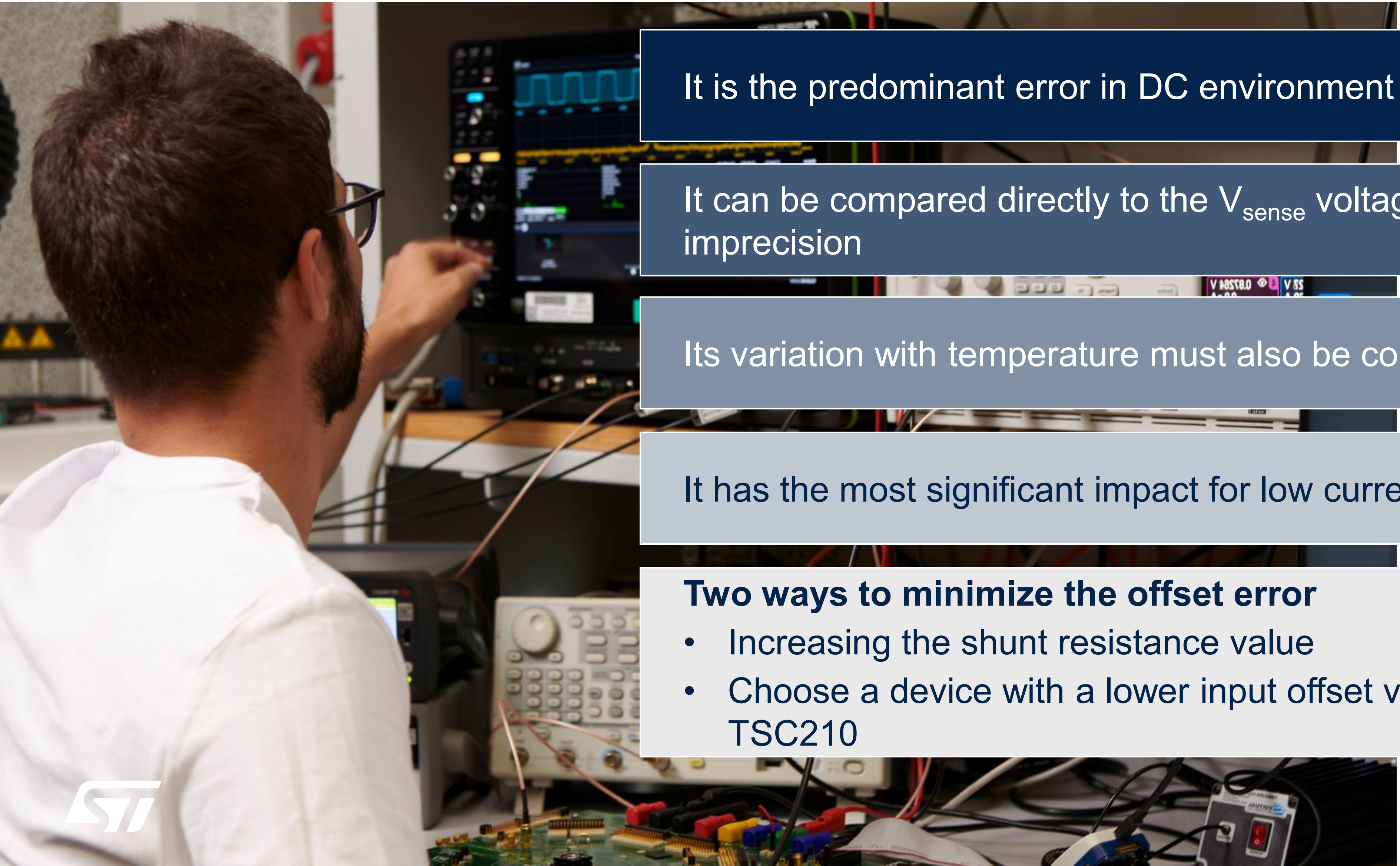
We now increase the temperature and include drift in the expression for V_{out}:

$$V_{out} = \left(V_{io} + \Delta T \cdot \frac{\Delta V_{io}}{\Delta T}\right) \times 100$$

This gives a good estimate of the worst-case output change due to V_{io} and its drift.
On the oscilloscope, the **TSC103** output offset increases from about $8\ \mathrm{mV}$ at $25°\mathrm{C}$ to about $18\ \mathrm{mV}$ at $125°\mathrm{C}$.
Consequently, using the **TSC103** would also require temperature calibration during manufacturing, which is costly.

In contrast, the **TSC214** is a zero-drift current-sensing amplifier. With a maximum $\Delta V_{io}/\Delta T$ of $300\ \mathrm{nV}/°\mathrm{C}$, its offset remains very low even over a wide temperature range, so this additional calibration step is generally unnecessary.

Input voltage offset error summary



It is the predominant error in DC environment

It can be compared directly to the V_{sense} voltage to define a first imprecision

Its variation with temperature must also be considered

It has the most significant impact for low current

Two ways to minimize the offset error

- Increasing the shunt resistance value
- Choose a device with a lower input offset voltage such as TSC240 or TSC210

Explanation

Input voltage offset error summary

Explanation of page 32

- The input offset voltage V_{IO} results from mismatches between internal circuit components and is always present, even in very precise devices.
- V_{IO} is a DC parameter and dominates the error when measuring small currents.
- A first estimate of the measurement error is simply the ratio V_{IO}/V_{SENSE}, where V_{SENSE} is the shunt voltage.
- Its temperature drift $\Delta V_{IO}/\Delta T$ must also be taken into account; selecting a device with low V_{IO} and low drift enables very accurate measurements without calibration.
- To improve accuracy at low currents, you can either:
  - increase the shunt resistance value, or
  - choose a current-sense amplifier with the lowest possible input offset voltage.

Our technology starts with You

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