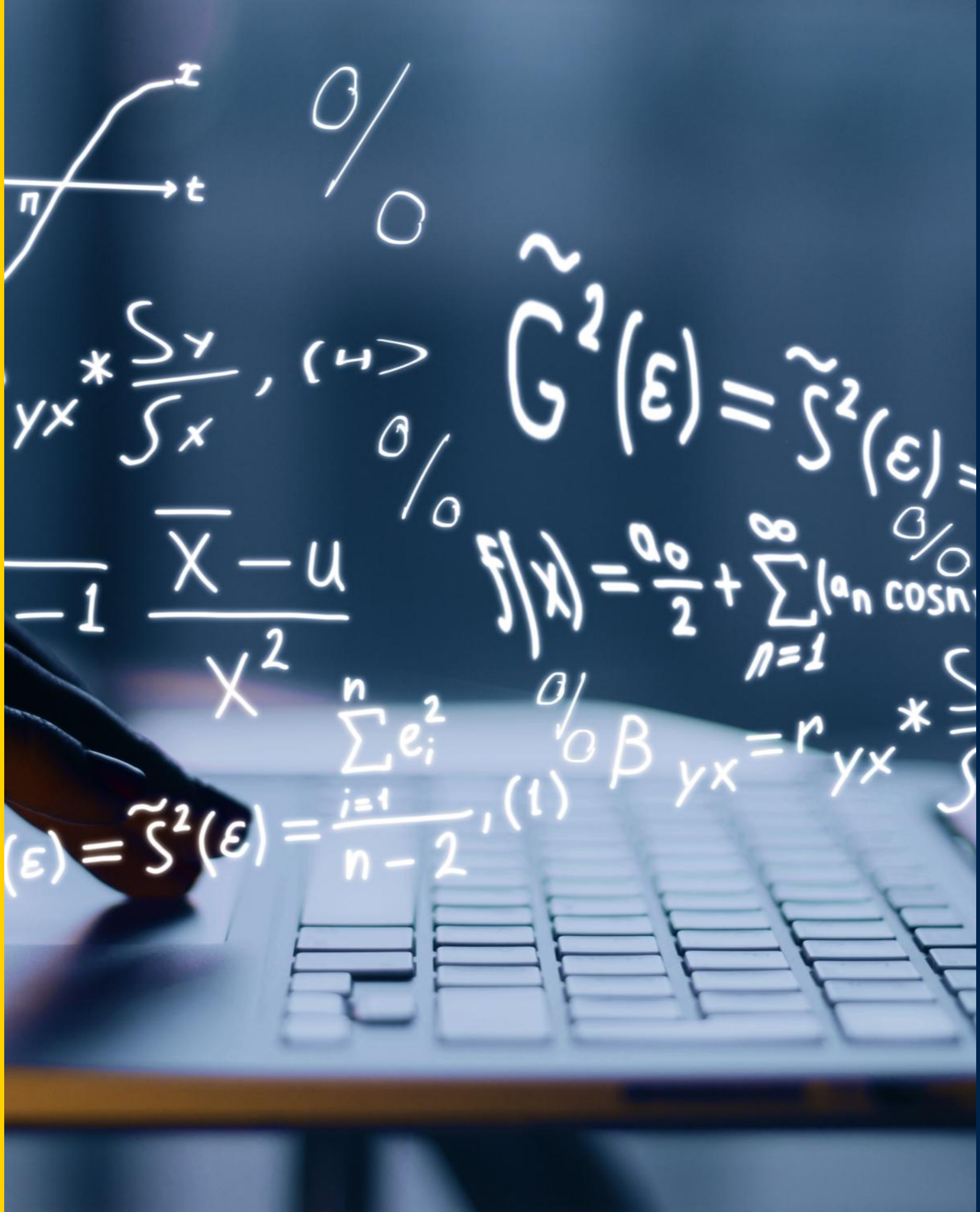
Exploring current sense amplifiers

STMicroelectronics Tech days



Error calculation methodology

Worst case

Statistical approach

User guide

This presentation provides a written explanation of the topic covered in the tenth chapter of the video: **"Error calculation methodology #10"**, which is available on our YouTube channel at the following link:

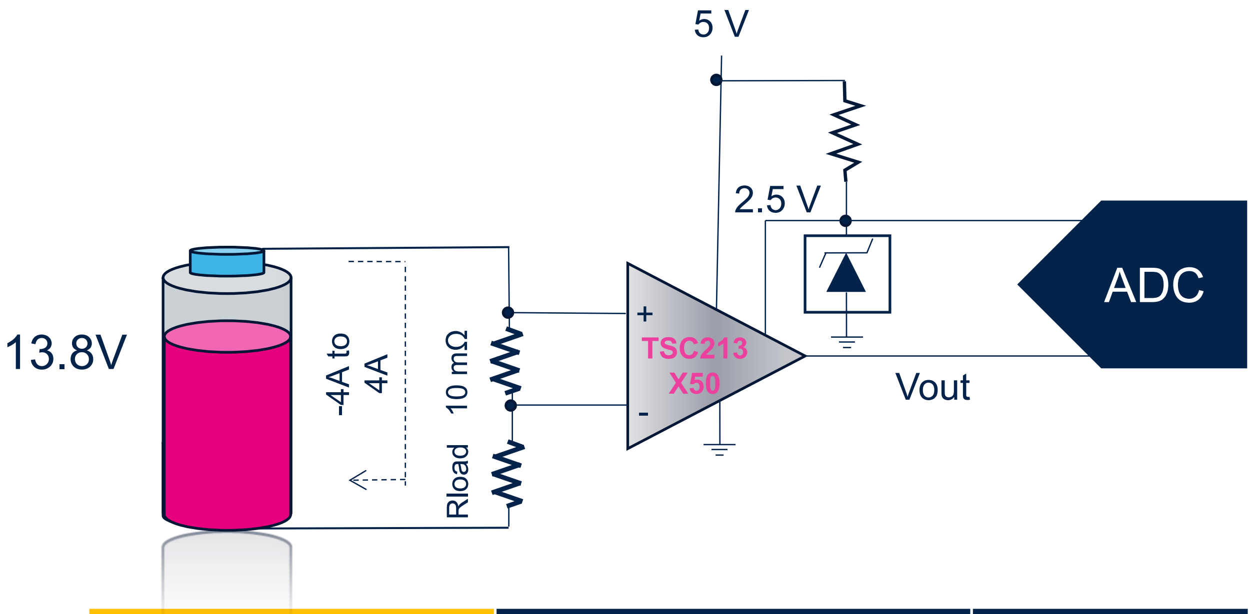
Video on YouTube

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)

Typical application using the TSC213 current sensing amplifier



	Calculation	Ideal ouptut voltage
Vout_min for I=100 mA	100 mA*10 mΩ*50+2.5 V	2.55 V
Vout_mx for I=4 A	4 A *10 mΩ*50+2.5 V	4.5 V

Parameter	Characteristic	Accuracy
V_{CC}	5V	
Vi_{cm}	13.8V	
Vref	2.5V	0.1%
Temperature	25°C to 125°C	
Shunt	10mΩ	0.5% accuracy a 100ppm/°C tempco 5µV/°C thermal EMF.
TSC213	Gain 50	1%

Typical application using the TSC213 current sensing amplifier

Explanation of page 4

To illustrate this point, start by defining an application.
The objective is to measure a bidirectional current delivered by a battery with a voltage of 13.8 V, ranging from −4 A to 4 A, using a shunt-based current sensing solution powered by 5 V. To limit power dissipation in the shunt, a value of 10 mΩ is selected.

A current sensing amplifier with a gain of 50 is required to exploit the full scale of the output voltage. For precise measurement, special care is taken with the shunt, and the **TSC213** precision current sensing amplifier is selected. The **TSC213** operates with a common-mode voltage up to 26 V and offers a maximum input voltage offset (Vio) of 100 µV.

We use an external 2.5 V voltage reference, such as the LM4040A, to set the output common-mode voltage in the middle of the output range.
The **TSC213** output voltage is then processed by a differential analog-to-digital converter (ADC).

This example focuses on accuracy in the positive current measurement range, between 100 mA and 4 A. The analysis of accuracy in the negative current range, between −100 mA and −4 A, is identical.
From a theoretical point of view, the expected output voltage of the **TSC213** is between 2.55 V and 4.5 V

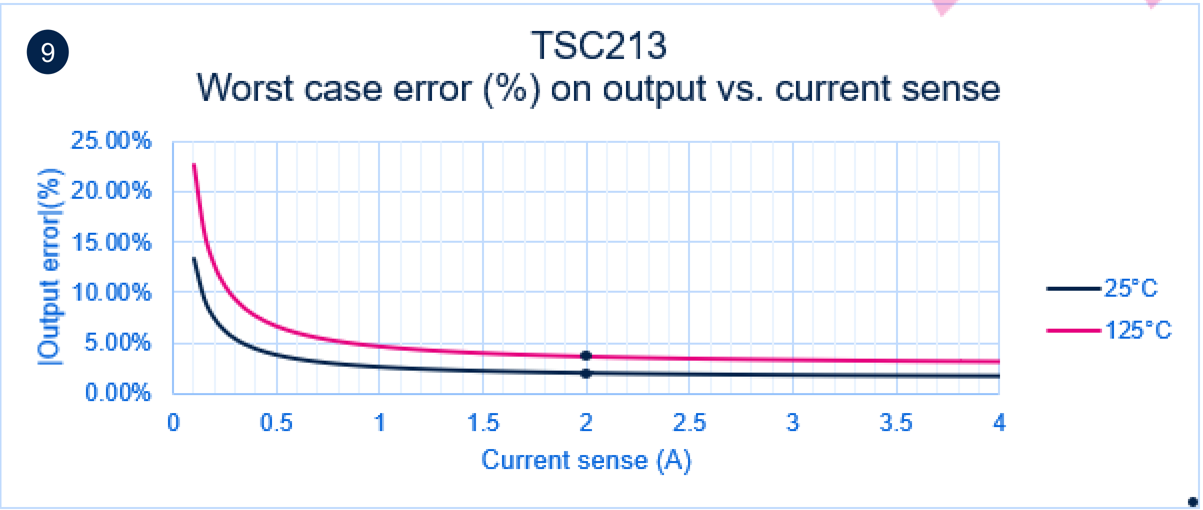
Worst-case-error estimation

$$Error_{max} = \overset{}{\frac{V_{io}}{R_{shunt}.I_{sense}}} + \frac{\left(\frac{dV_{io}}{dT}\right)*\Delta T}{R_{shunt}.I_{sense}} + \overset{1}{\frac{\frac{V_{icm}-12\,V}{CMRR}}{Rshunt.Isense}} + \overset{2}{\frac{\frac{Vcc_{Ds}-Vcc_{Sys}}{PSRR}}{R_{shunt}.I_{sense}}} + \overset{3}{\frac{Iib}{I_{sense}}} + \overset{4}{\frac{EMF*\Delta Te2e}{R_{shunt}.I_{sense}}} + \overset{5}{\varepsilon G + \frac{dG}{dT}*\Delta T} + \overset{6}{\varepsilon linearity} + \overbrace{\varepsilon shunt + \varepsilon shunt_{tempco}*\Delta T}^{7} + \overbrace{\cancel{\frac{\left(\frac{dV_{ref}}{dT}\right)*\Delta T}{R_{shunt}.I_{sense}}} + \cancel{\frac{V_{ref}.(\varepsilon ref)}{G.R_{shunt}.I_{sense}}}}^{8}$$

	Error source acting as an offset	Equation	Calculus	% error for I=2A @125°C
	Vio error	$V_{io} + \left(\frac{dV_{io}}{dT}\right)*\Delta T$	100µV+0.5µV/°C*100	0.8%
1	CMRR	$\frac{V_{icm}-12V}{CMRR}$	$\frac{13.8\,V-12\,V}{10^{\frac{100}{20}}}$	0.09%
2	PSRR	$\frac{Vcc_{Ds}-Vcc_{Sys}}{PSRR}$	$\frac{5\,V-5\,V}{10^{\frac{100}{20}}}$	0%
3	Input bias current	Iib	35µA	1.75ppm
4	Thermal EMF	$EMF*\Delta Te2e$	5 µV/°C*10°C	0.25%

Worst cases are very un-probable to happen

Total error = 3.65%



	Error source acting as a percentage	Equation	Calculation	% error for I=2A @125°C
5	Gain error	$G + \frac{dG}{dT}*\Delta T$	1%	1%
6	Nonlinearity	$\varepsilon Linearity$	0.01%	0.01%
7	Shunt error	$\varepsilon shunt + \varepsilon shunt_{tempco} * \Delta T$	0.5%+100ppm/(°C) * 100°C	1.5%

Worst-case-error estimation

Explanation of page 6

The simplest worst-case method is to add all error sources from the current sense amplifier and its external environment, such as the shunt and the voltage reference. Although very pessimistic, this approach helps estimate the maximum error. Here, the impact of each parameter is evaluated for a reference current of $2\ \mathrm{A}$.

As shown in the previous chapters, several error sources affect current measurement. We first consider the errors acting as an offset, which are the dominant contributors at low current.
The main contributor is the input offset voltage and its temperature drift. At $2\ \mathrm{A}$ and $125°\mathrm{C}$, the combination of V_{io} and $\frac{dV_{io}}{dT}$ adds an error of 0.8% relative to the theoretical current measurement expressed by $R_{shunt} \times I_{sense}$.

1. Another important parameter is the error due to CMRR, especially when the input common-mode voltage in the application differs from the value specified in the datasheet. In this example, the application operates at $V_{ICM} = 13.8\ \mathrm{V}$, while the TSC213 datasheet specifies input offset at $V_{ICM} = 12\ \mathrm{V}$. The CMRR therefore adds an error lower than 0.1% for a measured current of $2\ \mathrm{A}$ at $125°\mathrm{C}$.

Explanation of page 6

2 PSRR is evaluated in the same way as CMRR, but with respect to the supply voltage. In this example, $V_{CC} = 5\ \mathrm{V}$, which is the same as the datasheet test condition. Its impact is therefore null and can be neglected.

3 The input bias current can also affect measurement accuracy in some cases. For the TSC213, however, the input bias currents are very small and more than three decades below the minimum current to be measured, so their impact is negligible.

4 Another offset-type contributor comes from the external shunt resistor: the thermal EMF. This very small voltage, in the $\mu\mathrm{V}$ range, is generated by a temperature difference ΔT_{e2e} across the resistor. In this example, assuming about $10°\mathrm{C}$ temperature difference between the two ends of the shunt, thermal EMF adds about 0.3% error to the measurement of a $2\ \mathrm{A}$ current at $125°\mathrm{C}$.

After offset-related terms, we must also consider the errors acting as a percentage, which generally have a stronger impact at high current.

Worst-case-error estimation

5 The first and most important of these is the gain error. Since the gain is integrated inside the current sense amplifier, internal resistor matching must be as accurate as possible. Because gain error is already expressed as a percentage, its impact on the current measurement is straightforward to evaluate.

6 Linearity describes how constant the gain remains over the amplifier input range. In general, the linearity error is much smaller than the gain error and can often be neglected. In this example, its contribution is only 0.01%.

7 The shunt resistor tolerance must also be included, even though it is not correlated with the current sense amplifier itself, because it is part of the measurement chain. In this example, the selected shunt adds 1.5% error to the current measurement at $125°\mathrm{C}$.

8 One last term can be added for the output common-mode voltage, considered here as an offset-type error. The TSC213 is used in bidirectional mode, with the output common-mode level fixed by an external V_{ref}. In this example, the ADC measures both V_{ref} and V_{out} in differential mode, so the error linked to V_{ref} is cancelled.

Worst-case-error estimation

Explanation of page 6

9 By summing all error contributions from the current sense amplifier and the external components, the total output error of the TSC213 reaches 3.65% for a measured current of $2\ \mathrm{A}$ at $125°\mathrm{C}$.

At first glance, the full error equation may look long and complex. In practice, it is simply a summary of the main contributors, added step by step.

If the same calculation is repeated for each current point, the expected error can be plotted over the full current range. The plot shows that the percentage error is much higher at low current, mainly because of the offset-related terms.

To reduce the percentage error at low current, there are two options:

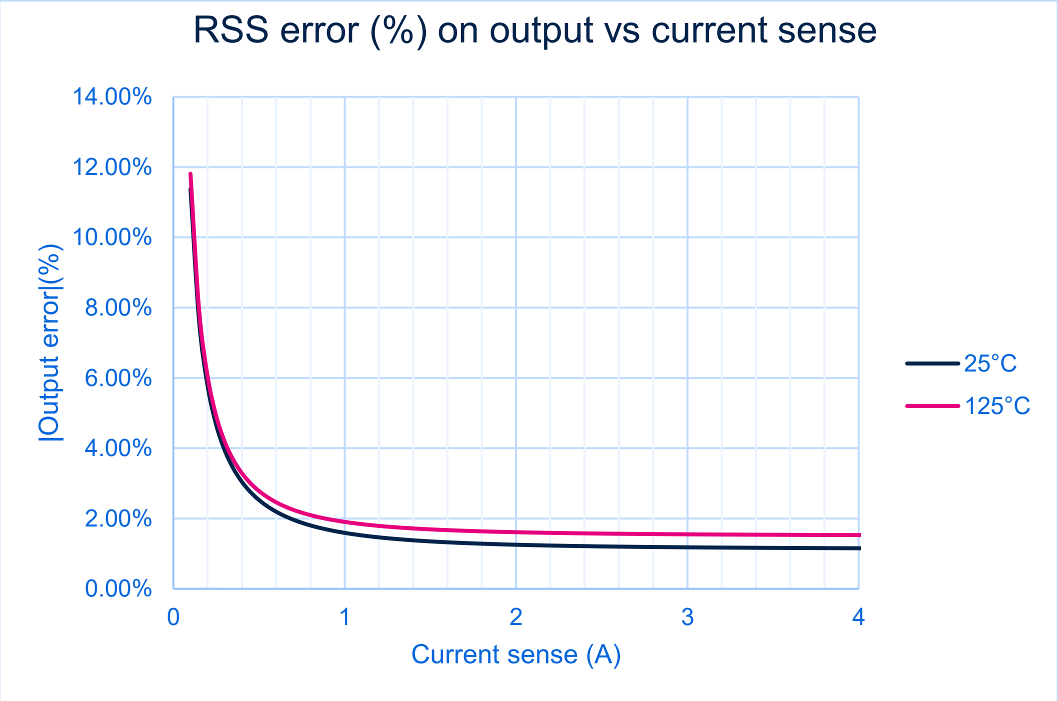
- increase the shunt resistor value, which raises the input voltage level and reduces the relative error;
- choose a current sense amplifier with better parameters than those listed here.

Once again, this calculation method is highly pessimistic and should be considered an extreme worst-case estimation.

Root-sum-square approximation

$$error\_Rss = \sqrt{\left(\frac{Vio}{Rshunt.I}\right)^2 + \left(\frac{\left(\frac{dVio}{dT}\right)*\Delta T}{Rshunt.I}\right)^2 + \left(\frac{\frac{Vicm-12V}{CMRR}}{Rshunt.I}\right)^2 + \left(\frac{\frac{Vcc_{Ds}-Vcc_{Sys}}{PSRR}}{Rshunt.I}\right)^2 + \left(\frac{Iib}{Isense}\right)^2 + \left(\frac{EMF*\Delta Te2e}{Rshunt.I}\right)^2 + (\varepsilon G)^2 + \left(\frac{dG}{dT}*\Delta T\right)^2 + (\varepsilon linearity)^2 + (\varepsilon shunt)^2 + \left(\varepsilon shunt_{tempco}*\Delta T\right)^2 + \left(\frac{\left(\frac{dV_{ref}}{dT}\right)*\Delta T}{R_{shunt}.I_{sense}}\right)^2 + \left(\frac{Vref.(\varepsilon ref)}{G.Rshunt.I}\right)^2}$$

Error source	Equation	Max datasheet
Input offset error	V_{io}	100µV
Input offset voltage drift error	$dVio/dT*\Delta T$	0.3µV/°C
CMRR error	$CMRR$	100000V/V
PSRR error	PSRR	100000V/V
Iib error	iib	35µA
Thermal EMF	EMF$*\Delta T$e2e	50µV
Gain error	εG	1%
Gain drift error	$dG/dT * \Delta T$	20 ppm/°C
Shunt error	$\varepsilon shunt$	0.5%
Tempco shunt	$\varepsilon shunt\_tempco * \Delta T$	100ppm/°C



an error of 1.7% is expected for a current of 2A @125°C.

Root-sum-square approximation

Explanation of page 11

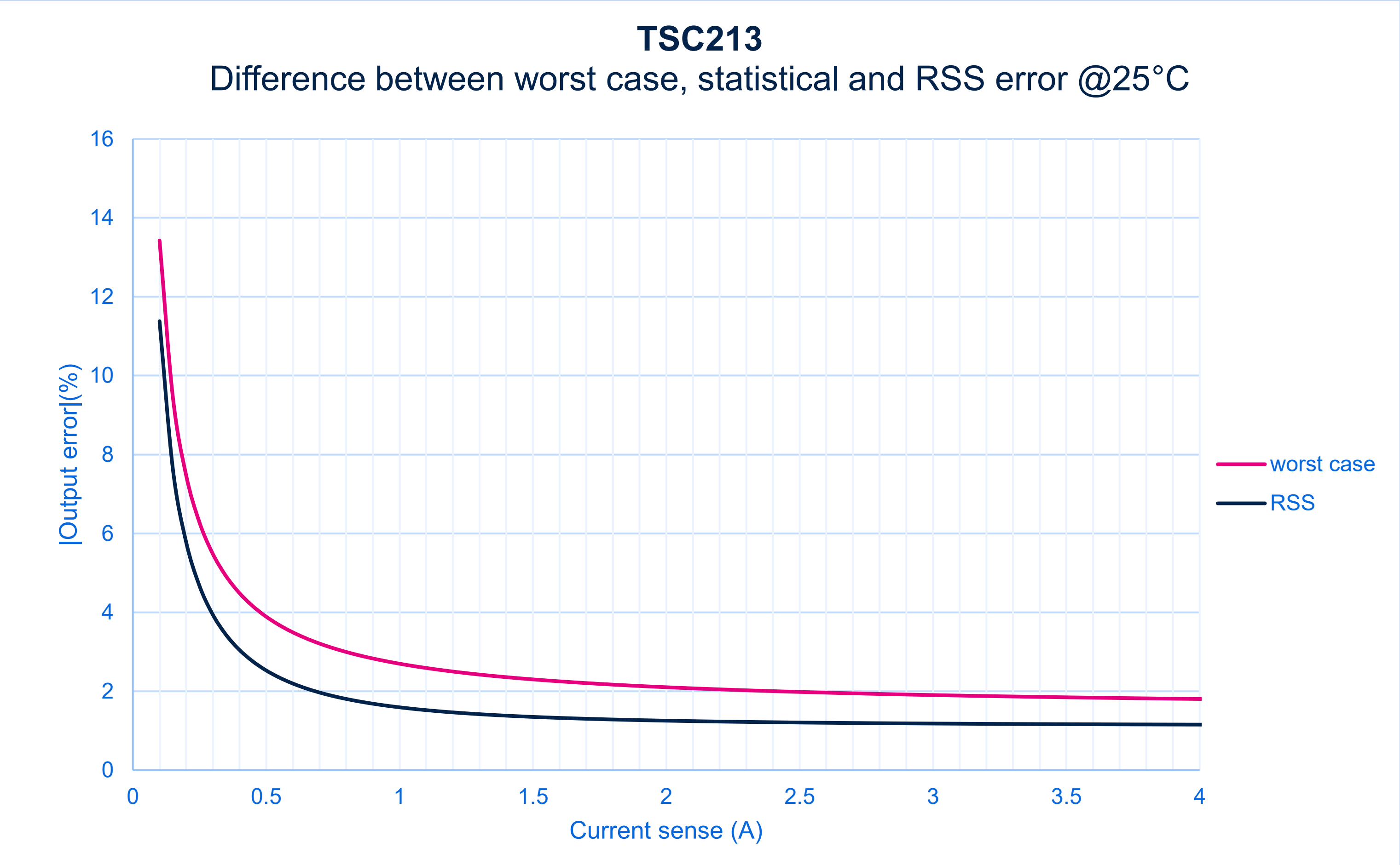
A more realistic approach is to use a statistical approximation. To estimate the maximum output error more accurately, the different error terms can be combined using the root-sum-of-the-squares, or RSS method.

This simplified statistical method is based on the same error sources as the worst-case calculation, but it assumes that the average value of each error term is zero and that the maximum values given in the datasheet have the same process capability index, or Cpk. Under the additional assumption that all error sources are uncorrelated, the RSS result gives an overall error with the same Cpk.

The list of contributors in the global error remains exactly the same as in the previous method. The difference is that, instead of being summed directly, the terms are combined through a quadratic sum.

With this approach, the estimated output error of the current sensing stage is $\mathbf{1.7}\%$ instead of $\mathbf{3.65}\%$ for a current of $\mathbf{2\ A}$ measured at $\mathbf{125°C}$.

Worst case, and RSS approach



- Worst cases are very unlikely to happen.
- RSS simplified approximation results based on statistics.

edesignSuite tool

Worst case, and RSS approach

Explanation of page 13

As shown in this chapter, two methods can be used to estimate the error on a current sensing measurement.

The first is a very conservative worst-case approach, which consists in summing all maximum parameter values from the current sense amplifier, the shunt, and the reference voltage datasheets. This method is highly pessimistic, but it provides large design margin and ensures that the estimated error should never be reached. In this example, the worst-case estimation is represented by the pink curve.

The second method, which is more realistic, is the statistical RSS approach, represented by the dark blue curve. The graph compares both estimation methods at $25°C$ for the example discussed in this chapter.

You can also use ST's **eDesignSuite** tool to estimate the error of a current sensing system using the RSS method. The tool allows you to select a current sense amplifier from the ST portfolio, enter the required measurement conditions and shunt characteristics, and automatically generate the corresponding error curve.

eDesignSuite - High side current sensing

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