AN5849

Application note

Expected output error for a current sensing amplifier

Introduction

Sensing the current flow is fundamental in many systems such as motor control, server equipment or baseband stations. The most familiar way to measure current is to sense the voltage drop across a shunt resistor. For applications using an extended input common mode voltage, let us say beyond the power supply of the op amp, this voltage drop can be conditioned by a dedicated current sensing amplifier. In order to not affect the current reading the shunt and the current sensing amplifier must be as precise as possible. Unfortunately, as nothing is perfect, all active or even passive electronics add their own identity, or error, in a system. This application note details all the parameters that might affect the current measurement and helps the designer to estimate the errors that can be expected on the output of a current sensing amplifier.

1 Error sources

1.1 Error sources acting as an offset

Several sources of error must be considered before starting a design. They usually tend to vary with temperature change. Let us start with some error contributors generally dominant when small current must be measured.

- **Input offset voltage**

The Vio is due to the inherent mismatch of the input transistors and components during fabrication of the silicon die, and the stress placed on the die during the packaging process (minor contribution). These effects collectively produce a mismatch of the bias of the input circuit, resulting in a differential voltage at the input terminals of the amplifier.

The error linked to the input offset on the output voltage can be written as equation 1, by considering the input offset voltage and its drift overtemperature:

$$Vio\ Error = \left(\pm Vio \pm \frac{dVio}{dT} * \Delta T\right) \tag{1}$$

It is interesting to consider this error on inputs versus the Vsense voltage across the shunt (Rshunt*Isense)

$$Vio\ impact\ (\%) = \frac{\pm Vio \pm \frac{dVio}{dT} * \Delta T}{Rshunt * Isense} * 100 \tag{2}$$

Depending on the expected error, a solution to improve accuracy is to increase the value of the shunt resistance Rshunt or choose a current sensing amplifier with a better (smaller) Vio and dVio/dT. With the first option, make sure to have a sufficient output swing to not saturate a full load.

- **Common mode rejection ratio**

The common mode rejection ratio is defined as the ratio of the differential voltage amplification to the common mode voltage amplification. This is measured by determining the ratio of a change in input common mode voltage, to the resulting change in the input offset voltage. The common mode input voltage affects the bias point of the input differential pair. Because of the inherent mismatches in the circuitry, changing the bias point changes the offset voltage, which in turn changes the output voltage.

In the electrical characteristics of the datasheet, Vio is generally specified at one input common mode voltage. So, one should consider the variation of the input voltage with the Vicm. Let us take Vicm = 12 V as a reference point, as it is specified for the TSC21x and TSC201x bidirectional current sensing amplifiers families.

The input referred error due to a common mode voltage variation can be written as equation 3:

$$CMRR\ error = \pm \frac{Vicm - 12V}{CMRR} \tag{3}$$

As for the Vio, let us refer this error to the sensed voltage (equation 4):

$$CMRR\ impact\ (\%) = \pm \frac{Vicm - 12V}{Rshunt * Isense * 10^{\frac{CMRR}{20}}} * 100 \tag{4}$$

The CMRR is an important point to consider, especially in applications such as motor control where it is susceptible to significant change. The Vio parameter is certainly a key point for accuracy criteria. But with poor CMRR, this advantage may be lost.

So, it is generally important to take into account the error induced by Vio, and by the CMRR, and these must be in the same order.

- **Power supply rejection ratio**

Power supply rejection ratio, PSRR is the ratio of power supply voltage change referred to as input offset voltage change. The power supply voltage affects the bias point of the input differential pair and is also responsible for an unwanted offset. The error term due to the PSRR can be calculated in the same manner as the CMRR parameter.

So, the error due to a power supply voltage variation can be written as equation (5):

$$PSRR\ error = \pm \frac{Vcc_{DS} - Vcc_{Sys}}{PSRR} \tag{5}$$

Where Vcc_{DS} is the power supply voltage at which the Vio is specified in the datasheet, and Vcc_{Sys} is the power supply of the op amp in the application.

As for the Vio, let us refer this error to the sensed voltage.

$$PSRR\ impact\ (\%) = \pm \frac{Vcc_{DS} - Vcc_{Sys}}{Rshunt*Isense*10^{\frac{PSRR}{20}}} * 100 \quad (6)$$

In most applications, the power supply of a current sensing is well regulated. In this case, the PSRR impact is extremely limited. Moreover, if the power supply is decoupled well, it limits a lot of the effect of the PSRR. So, this parameter is generally not considered in the error budget, except if the power supply is, for example, done by the common mode voltage; in this case it is important to add it in the total error equation.

1.2 Error sources acting as a percentage

Some other sources of errors act as a percentage, so they have a higher impact with higher sensed current.

- **Gain error**

Generally, the gain is already integrated in the current sense amplifier, allowing a better accuracy than external resistance use. Nevertheless, having a perfect match between resistances are extremely difficult; it results in a small error that can be considered in the error budget of a current sensing amplifier (Ɛgain). Normally the integrated resistances are made with the same material and thus should have the same temperature coefficient. Nevertheless, a very small gain drift ($\frac{dG}{dT}$) can happen during temperature variation and can be expressed by equation (7):

$$Gain\ error = Gain\,.\left(\varepsilon gain + \frac{dG}{dT} * \Delta T\right) \quad (7)$$

It is important to know that even if a current sensing amplifier is rail to rail, the gain error is defined in the datasheet for an output range, in which it is in the linear operating region. The gain error contributes to the total error budget in percentage and not as an offset as Vio, CMRR, or PSRR parameters.

- **Linearity error**

The linearity error expresses how the gain curve is linear. It is calculated in the datasheet as equation (8):

$$Linearity\ error = \frac{Vout_{measured} - Gain\left(best_{fitline}\right)*Vsense - Offset\left(best_{fitline}\right)}{Vout_{FullScale}} \quad (8)$$

Like the gain error, the linearity contributes to the total error budget in percentage and not as an offset as Vio, CMRR, or PSRR parameters.

Generally, the linearity error is largely smaller than the gain error and can be neglected. Nevertheless, as the gain error has been calculated thanks to the best fit line approach, it gives the information that the gain error can be relatively constant throughout the linear input range of the current sense amplifier.

It can make sense to consider this error in the total error budget in case of specific application where the gain is calibrated at production level.

- **Output common mode error**

In the case of a bidirectional current sense amplifier, it is possible to set the output common voltage either thanks to an external power supply or either thanks to an internal divider bridge when available. In any case, the inaccuracy of the reference voltage can be considered as an error directly on the output of the current sensing amplifier. It can be written as equation (9):

$$Vocm\ error = Vref\,.\,(\varepsilon Vref) \quad (9)$$

1.3 Error sources being application dependent

The last type of error that can be considered is mostly application dependent:

- **Input bias current error**

Usually the input bias current on current sense amplifiers are higher than op amps, from µA to several hundred of µA. It is mainly due to the architecture of the current sense amplifier, which can work with input common mode voltage largely beyond the power supply Vcc range. The first consideration is the current to be measured trough the shunt resistor, which must be much larger than the input bias current, otherwise the error due to the input bias current must be considered.

$$Iib\ impact(\%) = \frac{Iib}{Isense}*100 \tag{10}$$

Generally, in high current sensing applications, the focus is to reduce as much as possible the power dissipation ($Rshunt*Isense^2$) by choosing the smallest shunt value. But for high shunt resistance values, it is important to consider the input bias currents which can generate, with the shunt, a small offset on input as the input voltage offset (Vio).

$$Iib\ Error = (Iib*Rshunt) \tag{11}$$

This kind of error is mostly application dependent and can be neglected by sizing correctly the system.

- **Shunt resistance**

Mostly, the shunt resistor is not integrated to the current sense amplifier and so its electrical parameters are not described in the datasheet. However, the choice of the shunt is very important as it is a key contributor to the total budget error. Several points must be considered. The shunt tolerance generally expressed in % directly contributes to the gain error. So, 1% shunt accuracy automatically adds 1% error to the system. But another parameter must be considered, it is the variance of the resistance in temperature, generally named temperature coefficient resistance (TCR) or tempco expressed in ppm/°C.

In addition, another error can be added, related to the shunt. It is the thermal EMF, a very small voltage, in the range of µV, which is produced due to temperature variations (∆Te2e) across the resistor.

The offset error due to the shunt resistor expressed in volts can be written as equation (12):

$$Shunt\ error = Rshunt\left(\varepsilon shunt + \varepsilon shunt_{tempco}*\Delta T\right).(Isense) + (EMF*\Delta Te2e) \tag{12}$$

Where εshunt is the resistance tolerance in %

εshunt_tempco the resistance tempo in ppm/°C

EMF the thermal EMF expressed in µV/°C

And ∆Te2e the temperature difference between end to end connection of the shunt resistance.

2 Summing the errors

To calculate the total error added by the current sense amplifier we simply have to sum all the errors mentioned in the previous section, by considering all the maximum parameters of the datasheet. This approach is very pessimistic, and the chance to get all the maximum parameter values on a same die is extremely low, even null.

For a bidirectional current sense amplifier, the error at the output can be calculated as mentioned by equation (13):

$$Error_{max} = \frac{Vout\ max - Vout\ theo}{Vout\ theo - Vref} \tag{13}$$

With $Vout_{theo}$ = G . Rshunt . Isense + Vref

$$Vout_{max} = G\left(1 + \varepsilon G + \varepsilon Linearity + \frac{dG}{dT} * \Delta T\right).\left(Rshunt\left(1 + \varepsilon shunt + \varepsilon shunt_{tempco} * \Delta T\right).(Isense) + \left(Vio + EMF * \Delta Te2e + \left(\frac{dVio}{dT}\right) * \Delta T + Rshunt * Iib\right) + \left(\frac{Vcc_{Ds} - Vcc_{Sys}}{PSRR}\right) + \left(\frac{Vicm - 12V}{CMRR}\right)\right) + Vref.(1 + \varepsilon ref) \tag{14}$$

G: Gain

εG: gain error (%)

εLinearity: linearity error (%)

dG/dT: the gain variation over temperature

Rshunt: the value of the shunt resistance (Ω)

εshunt: shunt precision (%)

εshunt_tempco: the shunt tempco (ppm/°C)

Isense: the current to be measured (A)

Vio: input offset voltage (V)

EMF*ΔTe2e: offset related to thermal EMF of the shunt and temperature difference on the shunt end to end (V)

dVio/dT: offset drift vs. temperature (V/°C)

(VccDs-VccSys)/PSRR: the error due to PSRR (V)

(Vicm-12V)/CMRR: the error due to CMRR (V)

εref: error on Vref

We can also express the maximum total error expected

$$Error_{max} = \varepsilon G + \varepsilon linearity + \frac{dG}{dT} * \Delta T + \varepsilon shunt + \varepsilon shunt_{tempco} * \Delta T + \frac{Vio}{Rshunt.Isense} + \frac{EMF * \Delta Te2e}{Rshunt.Isense} + \frac{\left(\frac{dVio}{dT}\right) * \Delta T}{Rshunt.Isense} + \frac{Iib}{Isense} + \frac{\frac{Vcc_{Ds} - Vcc_{Sys}}{PSRR}}{Rshunt.Isense} + \frac{\frac{Vicm - 12V}{CMRR}}{Rshunt.Isense} + \frac{Vref.(\varepsilon ref)}{G.Rshunt.Isense} \tag{15}$$

It is quite a complex equation for a small current sense amplifier so let us take an example to better understand with numbers what can happen on the output of the current sense amplifier when we simply want to measure a current through a resistance, and normally only need ohm law.

In a solenoid control application, the current must be measured on the battery of 13.8 V. The application constraint is detailed below:

- Vcc = 5 V
- Vicm = 13.8 V
- Vref = 2.5 V is provided by an external power supply with an accuracy of 0.1%
- Temperature = 25 °C to 125 °C
- Current to measure 100 mA to 4 A
- Shunt 10 mΩ with 0.5% accuracy and a tempco of 100 ppm/°C and 5 µV/°C as thermal EMF
- A temperature difference between both connections of the shunt is 10 °C
- The TSC213 bidirectional current sensing with a gain of 50 is used.

Let us take one current point, 2 A, and @125 °C in order to see the impact of each parameter on the error budget.

2.1 Worst-case error budget

From the above equations let us detail all the error terms by using the maximum value of the electrical characteristic (when available), in order to express as much as possible, the worst-case condition at 125 °C. This is definitely the worst-case scenario that should never be reached.

The errors expressed in Table 1 act as an offset voltage and have generally more impact at low current level. The % error is expressed with regard to a theoretical Vsense = 2 A * 10 mΩ = 20 mV.

Table 1. Error sources acting as an offset

Error source	Equation	Calculus	% error @125 °C
Vio error	$Vio + \left\|\left(\frac{dVio}{dT}\right) * \Delta T\right\|$	100 µV + 0.3 µV / °C * 100	0.7 %
Thermal EMF	$\|EMF * \Delta Te2e\|$	5 µV / °C * 10 °C	0.3 %
Input bias current	$Rshunt * \|Iib\|$	10 mΩ * 35 µA	0.18 ppm
PSRR	$\frac{\|Vcc_{Ds} - Vcc_{Sys}\|}{PSRR}$	$\frac{5V - 5V}{10^{\frac{100}{20}}}$	0 %
CMRR	$\frac{\|Vicm - 12V\|}{CMRR}$	$\frac{13.8V - 12V}{10^{\frac{100}{20}}}$	0.09 %
VOCM	$\frac{\varepsilon ref * \|Vref\|}{Gain}$	$\frac{0.1\% * 2.5V}{50}$	50 ppm
Total			1.1 %

The errors expressed in Table 2 generally have more impact at high current level.

Table 2. Error sources acting as a percentage of the measured current

Error source	Equation	Calculus	% error @125 °C
Gain error	$\varepsilon G + \frac{dG}{dT} * \Delta T$	$1\% + \frac{10\text{ppm}}{°\text{C}} * 100°\text{C}$	1.1 %
Non linearity	$\varepsilon Linearity$	0.01%	0.01 %
Shunt error	$\varepsilon shunt + \varepsilon shunt_{tempco} * \Delta T$	$0.5\,\% + \frac{100\text{ppm}}{°\text{C}} * 100°\text{C}$	1.5 %
Total			2.61 %

For a current to measure of 2 A @125 °C, it can be expected in worst-case conditions a total error of 3.7%.

Thanks to equation 15 the worst-case error on the output of the TSC213 current sensing can be detailed for the full current range as depicted by Figure 1.

Figure 1. Worst-case error (%) on output vs. input current sense

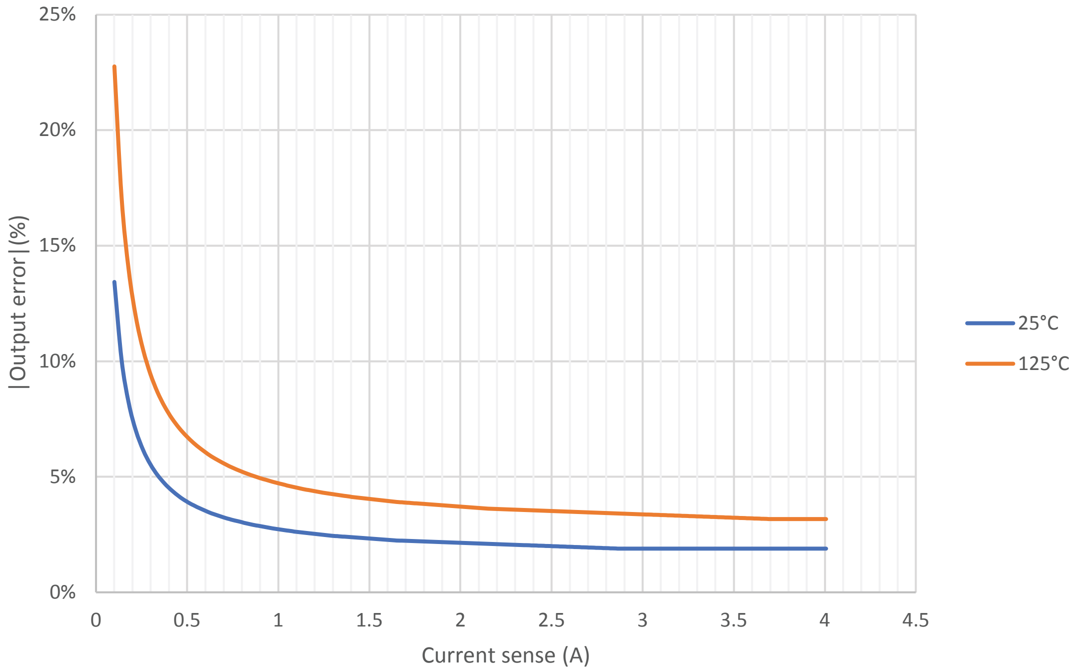


Figure 1 clearly demonstrates that the error increases when low current must be measured, because the parameters in Table 1 have more impact. And for higher current level the error tends to be constant as the parameters in Table 2 are predominant and constant.

3 Statistical error budget

As discussed in the previous section, the worst-case calculus is a very pessimistic approach, and the possibility to get all the maximum errors concentrated on a same die is extremely low, even null. So, a more realistic calculation is to use a statistical approach. This method is based on the average and the sigma of each parameter, to calculate the error of a current sense amplifier. It gives a better representation of the expected error.

Still considering equation 14, in this case, rather than using the max. parameters of the datasheet to calculate the error, we consider that the parameters follow a normal distribution and are uncorrelated. So we use the sum of the average of each parameter and the quadratic sum of the standard deviation of each parameter:

$$Error = \frac{\sum average + k*\sqrt{\sum sigma^2}}{G*Rshunt*Isense} \quad (16)$$

The k constant represents the number of the standard deviation accepted.

- ±3 σ represent 93.3% of the population
- ±4 σ represent 99.4% of the population
- ±5 σ represent 99.98% of the population
- ±6 σ represent 99.9997% of the population

This method is certainly more difficult to apply as the average and the sigma of each parameter are not clearly communicated. Nevertheless, in the typical characteristics, when available, some distribution graphs can be used to deduce this value. These graphs give a representation of the production at a certain moment and cannot be taken as a guarantee but can give a good idea.

In the previous section it has been seen that some parameters have an extremely low impact on the error budget. This is true for the input bias current, PSRR, or even linearity. So it can be neglected, and a focus can be done on the input offset voltage, CMRR, Gain and the shunt which most contribute to the error.

Simplifying equation14, in this case to calculate the statistical error on the output, the following equation 17 is used:

$$Vout - vout\ theo = G\left(\varepsilon G + \frac{dG}{dT}*\Delta T\right).Rshunt*Isense + G\left(Rshunt\ .\left(\varepsilon shunt + \varepsilon shunt_{tempco}*\Delta T\right).\right.$$
$$\left. Isense + \left(Vio + EMF*\Delta Te2e + \frac{dVio}{dT}*\Delta T\right) + \left(\frac{Vicm - 12V}{CMRR}\right)\right) \quad (17)$$

G: gain

εG: gain error (%)

dG/dT: the gain variation overtemperature

Rshunt: the value of the shunt resistance (Ω)

εshunt: shunt precision (%)

εshunt_tempco: the shunt tempco (ppm/°C)

Isense: the current to be measured (A)

Vio: input offset voltage (V)

EMF*ΔTe2e: offset related to thermal EMF of the shunt and temperature difference on the shunt end to end (V)

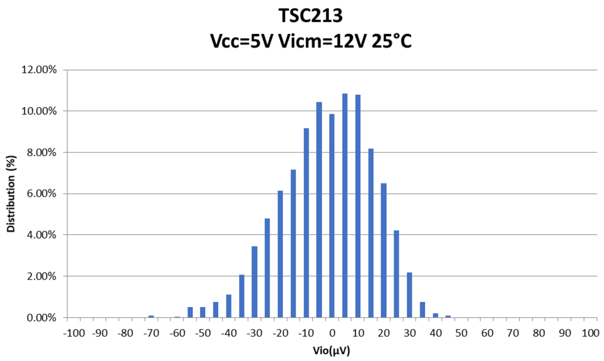
dVio/dT: offset drift vs. temperature (V/°C)

(Vicm-12V)/CMRR: the error due to CMRR (V)

Let us take the same application example as the previous section (the worst-case error budget calculation). The following distribution is useful to deduce the average and the sigma (σ).

Regarding the shunt parameter, the distribution data can be found in the datasheet of the component. In this calculation we assume a CPK of 2 for the shunt parameter (the maximum specification is at 6σ).

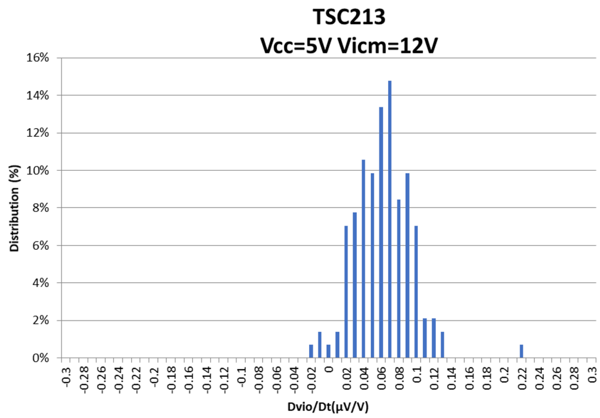
Figure 2. Input offset voltage distribution



Average: - 4.4 µV

σ = 18 µV

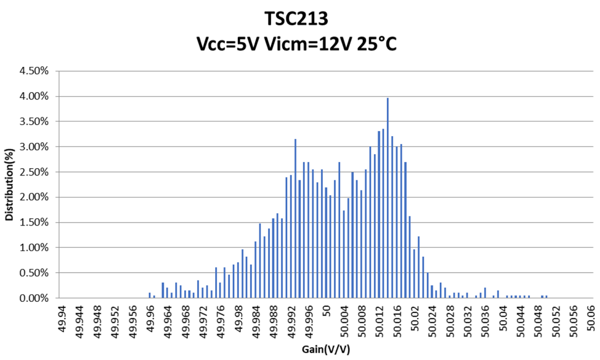
Figure 3. Input voltage offset drift vs. temperature distribution



Average: 0.06 µV/°C

σ = 0.04 µV/°C

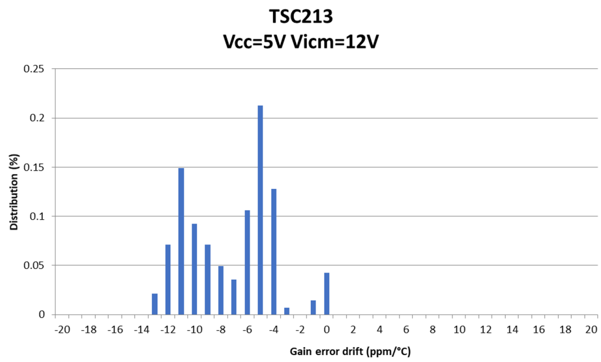
Figure 4. Gain distribution



Average: 50

σ = 0.01

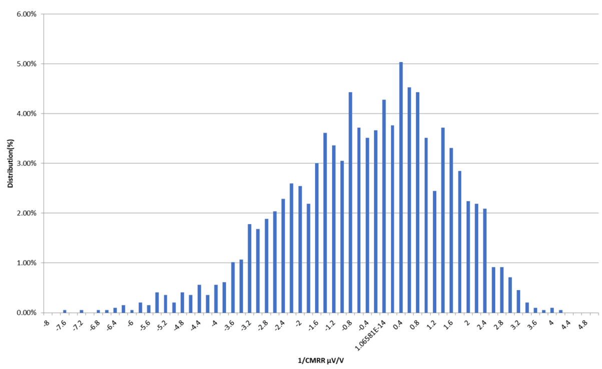
Figure 5. Gain error drift vs. temperature distribution



Average: - 7.7 ppm/°C

σ = 3.3 ppm/°C

Figure 6. 1/CMRR error distribution



Average: - 0.5 µV/V

σ = 1.9 µV/V

Let us detail the statistical error calculation in the following Table 3 for a current flowing into the shunt of 2 A at 125 °C.

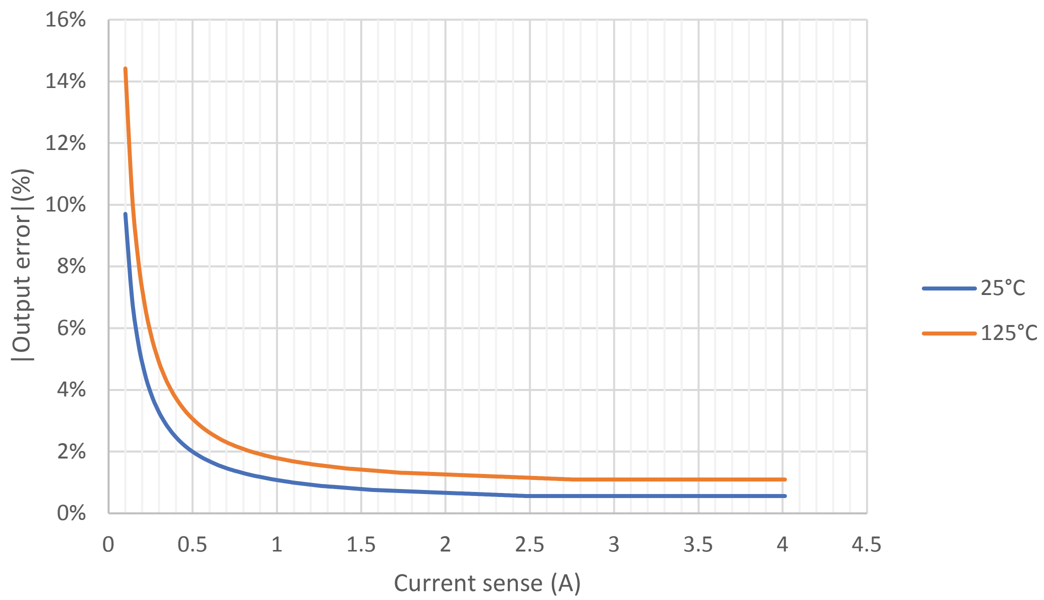
Table 3. **Average and sigma of each parameter for a 2 A current at 125 °C**

Error source	Equation	Average	Sigma
Gain error	$G^*\varepsilon G^*Rshunt^*Isense$	0*10mΩ*2A = 0V	0.01*10mΩ*2A = 200µV
Gain drift error	$G * dG/dT * \Delta T * Rshunt * Isense$	50*-7.7ppm/°C*100*10mΩ*2A = -770µV	50*3.3ppm/°C*100*10mΩ*2A = 330µV
Shunt error	$G^*\varepsilon shunt^*Rshunt^*Isense$	50*0*10mΩ*2A = 0µV	50*833e-6*10mΩ*2A = 833µV
Tempco shunt	$G^*\varepsilon shunt_{tempco}{}^*\Delta T^*Rshunt^*Isense$	50*0 *100*10mΩ*2A = 0µV	50*17e-6 *100*10mΩ*2A = 1.7mV
Input offset error	G*Vio	50*-4.4µV = -220µV	50*18µV = 900µV
Thermal EMF	G*EMF*∆Te2e	50*50µV = 2.5mV	50*0 = 0V
Input offset voltage drift error	$G * dVio/dT * \Delta T$	50*0.06µV/°C*100 = 300µV	50*0.04µV/°C*100 = 200µV
CMRR error	$G^*\frac{Vicm - 12V}{CMRR}$	50*(13.8V-12V)*-0.5µV/V = -45µV	50*(13.8V-12V)*1.9µV/V = 171µV

By using equation 16 and if we consider for this example a 5-sigma margin (i.e. k = 5), we can expect, for a current of 2 A, an error of 1.24% @125 °C.

Thanks to equation 17, the statistical error on the output of the TSC213 current sensing can be detailed for the full current range as depicted by Figure 7.

Figure 7. **Output statistical error (%), with a 5 sigma margin, vs. input current sense**



Like Figure 1, Figure 7 demonstrates that at low current, the errors related to the Vio and CMRR are predominant; this matter is independent of the mathematical approach. But we can see that the error expected in this case is largely better (1.24%), than the worst-case calculation (3.8%), and, above all, more realistic. This is for a 5-sigma margin, meaning that 100 ppm of the population can be beyond this error.

4 Root sum square approximation

The statistical approach seen previously offers a good approach of the global error expected on the output. But to be able to realize the whole calculation the user must have all the statistical curves available for each parameter in the datasheet.

Nevertheless, in order to have a good picture of the maximum possible error on the output, we can use a simplified statistical method based on the previous one, but with approximation errors. Total error can be determined by using the root-sum-of-the-squares (RSS), a method to combine the error terms. With this approach we consider that the average values are zero, and that the maximum parameter values given in the datasheet have all the same Cpk (the max. is given for all values with the same sigma) max. = K*sigma.

So, the error can be written as equation 18.

$$Error = \sqrt{\sum k\,.\,sigma^2} = \sqrt{\sum (\max datasheet)^2} \quad (18)$$

In this case, to calculate the statistical error on the output based on RSS approximation the following equation 19 is used:

$$Error\_Rss = \sqrt{\left((\varepsilon G)^2 + (\varepsilon linearity)^2 + \left(\frac{dG}{dT} * \Delta T\right)^2 + (\varepsilon shunt)^2 + \left(\varepsilon shunt_{tempco} * \Delta T\right)^2 + \left(\frac{Vio}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{EMF * \Delta Te2e}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{\left(\frac{dVio}{dT}\right) * \Delta T}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{Rshunt * Iib}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{\frac{Vcc_{DS} - Vcc_{Sys}}{PSRR}}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{\frac{Vicm - 12V}{CMRR}}{Rshunt\,.\,Isense}\right)^2 + \left(\frac{Vref\,.\,(\varepsilon ref)}{G\,.\,Rshunt\,.\,Isense}\right)^2\right)} \quad (19)$$

εG: gain error (%)

εlinearity: non linearity error

dG/dT: the gain variation overtemperature

εshunt: shunt precision (%)

εshunt_tempco: the shunt tempco (ppm/°C)

Isense: the current to be measured (A)

Vio: input offset voltage (V)

EMF*ΔTe2e: offset related to thermal EMF of the shunt and temperature difference on the shunt end to end (V)

dVio/dT: offset drift vs. temperature (V/°C)

(Vicm-12V)/CMRR: the error due to CMRR (V)

(VccDS − VccSys)/PSRR: the error due to PSRR (V)

εref: error on Vref

Let us take the same application example as the previous section (worst-case error budget calculation) and complete the following table with information available in the datasheet on TSC213. The calculation for each parameter is realized for a Isense current of 2 A at a temperature of 125 °C.

Table 4 is similar to Table 1. The main difference in the RSS method, is that the error is computed following a quadratic sum.

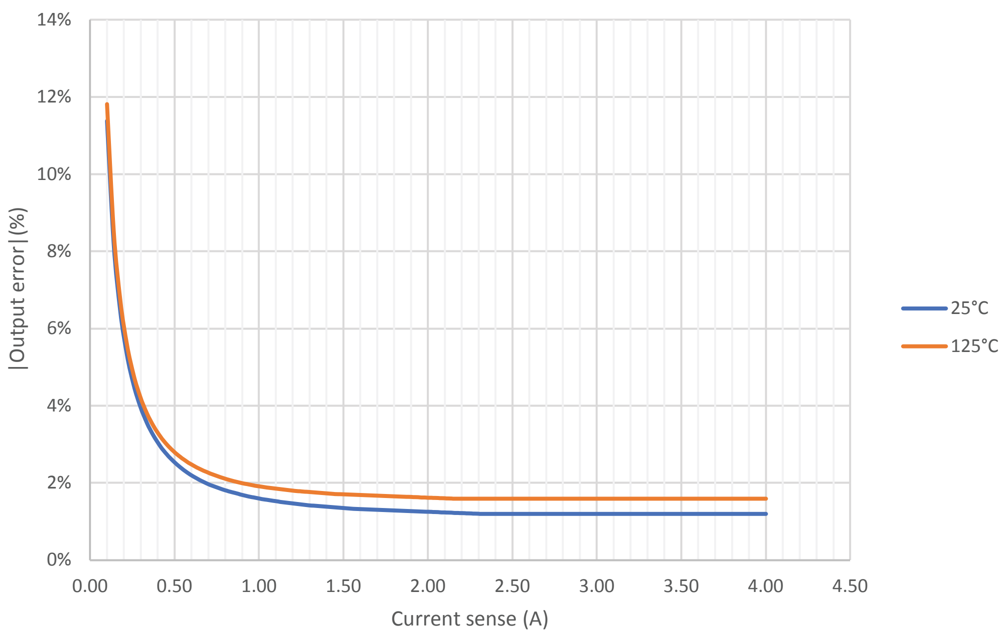
Table 4. Max error for each parameter for a 2 A Isense current @125 °C

Error source	Equation	Calculus	Max. datasheet @125 °C
Gain error	εG	1%	1%
Gain drift error	$\frac{dG}{dT} * \Delta T$	$\frac{20\text{ppm}}{°\text{C}} * 100°\text{C}$	0.20%
Shunt error	$\varepsilon shunt$	0.5%	0.5%
Tempco shunt	$\varepsilon shunt_{tempco} * \Delta T$	$\frac{100\text{ppm}}{°\text{C}} * 100°\text{C}$	1%
Input offset error	$\frac{Vio}{Rshunt\,.\,Isense}$	$\frac{100\mu V}{10m\Omega * 2A}$	0.5%
Thermal EMF	$\frac{EMF * \Delta Te2e}{Rshunt\,.\,Isense}$	$\frac{5\mu V/°C * 10°C}{10m\Omega * 2A}$	0.3%
Input offset voltage drift error	$\frac{\left(\frac{dVio}{dT}\right) * \Delta T}{Rshunt\,.\,Isense}$	$\frac{0.3\mu V/°C * 100°C}{10m\Omega * 2A}$	0.2%
PSRR error	$\frac{\frac{Vcc_{Ds} - Vcc_{Sys}}{PSRR}}{Rshunt\,.\,Isense}$	$\frac{\frac{5V - 5V}{10^{\frac{100}{20}}}}{10m\Omega * 2A}$	0%
CMRR error	$\frac{\frac{Vicm - 12V}{CMRR}}{Rshunt\,.\,Isense}$	$\frac{\frac{13.8V - 12V}{10^{\frac{100}{20}}}}{10m\Omega * 2A}$	0.09%
Vref error	$\frac{\varepsilon ref * \lvert Vref \rvert}{G\,.\,Rshunt\,.\,Isense}$	$\frac{0.1\% * 2.5V}{50 * 10m\Omega * 2A}$	50ppm

With an RSS statistical approach, we can expect, for a current of 2 A, an error of 1.61% @125 °C.

Thanks to equation 19, the statistical error on the output of the TSC213 current sensing can be detailed for the full current range as depicted by Figure 8.

Figure 8. Output statistical error (%), based on RSS approach, vs. input current sense



5 Conclusion

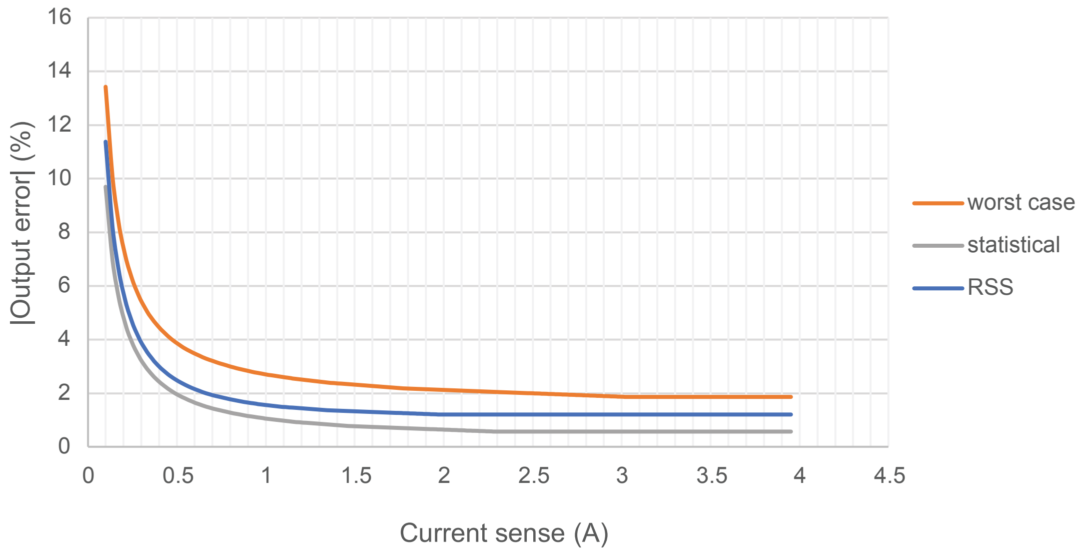
Evaluating the error budget is extremely important when using a current sense amplifier. It allows to size the system dealing with the right shunt and the right current sense amplifier. To realize it, several ways to calculate the total error on the output can be used. A very conservative approach consists of adding all the maximum values of each parameter of the datasheet. This method can be considered as a worst case and a very pessimistic approach, as the chance to get all the worst-case values on a same die is extremely low, even null.

Parameters described in the datasheet have a distribution and the error can be treated following a statistical approach. This method is based on the average and the sigma of each parameter to calculate the error on the output of the current sensing amplifier. It is a more realistic approach and, to have a very good representation, the calculation can be done for different Cpk. But distribution data of all parameters are not always well described in the datasheet.

A good compromise, to have a realistic and easy way to estimate the output error, is to use root sum square approximation method, which is a simplified statistical approach.

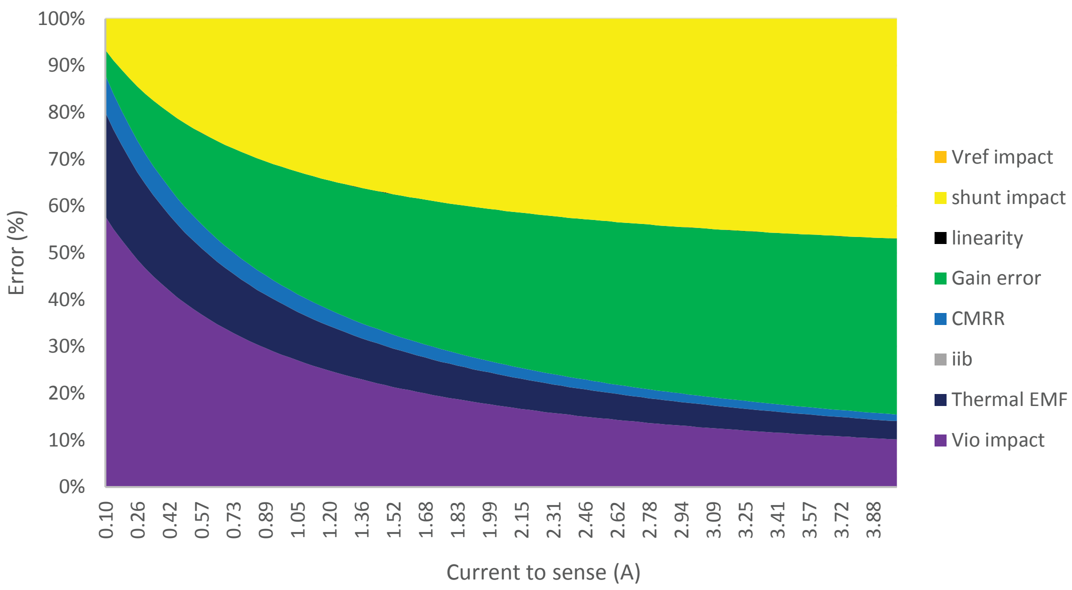
In this application note an example has been used to illustrate this purpose. Figure 9 shows the difference of error on the output of a current sensing using the three methods.

Figure 9. Statistical, RSS and worst-case approaches @ 25 °C



It has been demonstrated that each parameter has a predominant effect depending on the current level to be measured. Figure 10 summarizes the contribution of each parameter in the overall error, based on the worst-case calculus.

Figure 10. **Contribution of each parameter in the overall error**



For this use case, Figure 10 demonstrates the high impact of the input offset voltage Vio, on the total error when the current to measure is low. Whereas for higher current, this is the gain and shunt accuracy which have the biggest impact on the total error.

As a reminder, the statistical approach is based on production data which gives a picture of the production at a certain moment and it cannot be taken as a guarantee, only a good idea of what the error can be. Only the worst-case calculation gives a guarantee that the error will be lower than the obtained results.

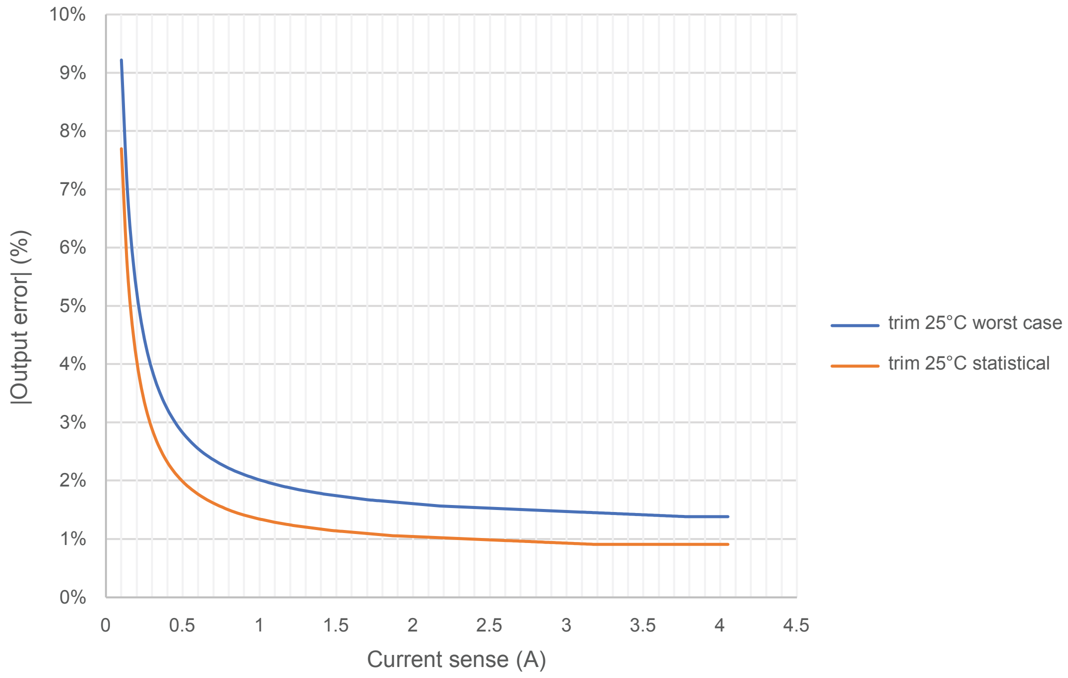
To finish, we can also consider a calibration at system production level at 25 °C. In this case only the parameters which have a drift in temperature, such as the dVio/dT, the dG/dT and the shunt tempco, play a role in the error budget.

In this case the output voltage error of the current sensing can be written by equation (20):

$$Vout\_error = G\left(\frac{dG}{dT} * \Delta T\right) . \left(Rshunt\left(\varepsilon shunt_{tempco} * \Delta T\right) . \left(Isense\right) + \left(\frac{dVio}{dT}\right) * \Delta T\right) \quad (20)$$

Using a zero drift current sense amplifier such as the TSC213 allows you to significantly decrease the total error on the output as Figure 11 shows.

Figure 11. **Error expected at 125 °C when the system is calibrated at 25 °C**



For a measured current of 2 A when the output of the TSC213 is calibrated at 25 °C with zero current, a max. error of 1% is expected at 125 °C by using a statistical approach. (1.25% without calibration).

The same case using worst-case analysis leads to 1.6% (while it is 3.7% without calibration).

Revision history

Table 5. Document revision history

Date	Version	Changes
17-Oct-2022	1	Initial release.

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