HOW TO ANALYZE AND COMPARE ALLEGRO CURRENT SENSOR AND ADC ERROR COMPONENTS

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INTRODUCTION

Allegro offers a wide variety of current sensors with analog voltage outputs, and in many applications, an analog-to-digital converter (ADC) converts the output voltage to a binary code. There are several error sources to consider in both the current sensor and ADC, that are all presented differently:

- Sensor offset error (in mV) is an output referred voltage
- Sensor sensitivity error (in %) is relative to the input current
- Sensor noise density is input referred in current at a particular frequency
- Sensor RMS noise can be either input referred in current or output referred in voltage
- ADC errors are often referred in LSBs

It is advisable to convert all these errors to input referred errors (in Amps) for easier analysis. This application note will explain how to convert all these errors to input referred and how the errors present in the binary code.

Allegro Current Sensors are factory set for a particular input current range (I_{PR}). In this application note, the ACS71240LLCTR-010B3 and ACS71240LLCTR-050B5 will be used as examples. The relevant performance specifications for this application note from the ACS71240 datasheet are listed in the Table 1. For information on the ACS71240, please refer to the Allegro website.

The maximum error specifications are specified for when the current sensor output is within 10% to 90% of the nominal supply voltage, not rail-to-rail. ADCs often will have a rail-to-rail input range that is equal to the supply voltage. Therefore, the ADC input and sensor output do not match. However, the ADCs are generally much higher accuracy than the sensor and not matching the voltage ranges will not affect the overall system accuracy.

Table 1: Summary of Relevant ACS71240 Performance Specifications

Characteristic	ACS71240LLCTR-010B3	ACS71240LLCTR-050B5
Input Current Range [I_{PR}]	±10 A	±50 A
Sensitivity [Sens]	132 mV/A	40 mV/A
Quiescent Voltage Output [V_{QVO}]	1.65 V	2.5 V
Nominal Supply Voltage [V_{CC}]	3.3 V	5 V
Output Operating Range [V_{OOR}]	0.33 to 2.97 V	0.50 to 4.50 V
Quiescent Voltage Output Error [V_{QVO_E}, –25°C to 125°C]	±15 mV (max)	±15 mV (max)
Sensitivity Error [E_{SENS}, 25°C to 125°C]	±2% (max)	±2% (max)
Noise Density [N_D]	100 µA/√Hz, V_{CC} = 5 V 150 uA/√Hz, V_{CC} = 3.3 V	
Noise [N]	52 mA_{RMS}, V_{CC} = 5 V 78 mA_{RMS}, , V_{CC} = 3.3 V	

ADC Resolution and Accuracy

The ADC resolution is defined as the smallest input voltage change that causes a change in the digital output code, 1 LSB (Least Significant Bit). The input referred LSB size in Amps can be determined by equation 1.

$$\mathrm{LSB\ (A)} = \frac{\mathrm{ADC\ input\ range\ (mV)}}{\mathrm{Sens}\left(\frac{\mathrm{mV}}{\mathrm{A}}\right) * 2^{n}}$$

Equation 1: LSB in mV to A Calculation

Where *n* is the number of bits of the converter and *Sens* is the sensor nominal sensitivity in mV/A.

Table 2 shows the ADC resolution of LSB size in Amps for a single-ended 12-bit ADC with rail-to-rail inputs, as are commonly found in microcontrollers.

Table 2: ADC Resolution of LSB size in Amps

ADC Input Range	12-bit ADC Resolution (LSB Size)	
	ACS71240LLCTR-010B3	ACS71240LLCTR-050B5
3.3 V	6.1 mA	20.0 mA [1]
5 V	9.3 mA	30.5 mA

[1] Sensor output range exceeds ADC input range

ADC inaccuracy can be defined by the differential non-linearity (DNL) and integral non-linearity (INL) of the device. Refer to Figure 1 for an illustration of DNL and INL. The DNL error is defined as the variation of each change in the ADC output from the ideal LSB size, usually specified on the ADC datasheet relative to the LSB size. The INL is defined as the error between the input voltage and the ideal expected output digital code. The INL can be thought of as the cumulation of DNL errors. The ADC specification sheet can specify INL in number of LSBs.

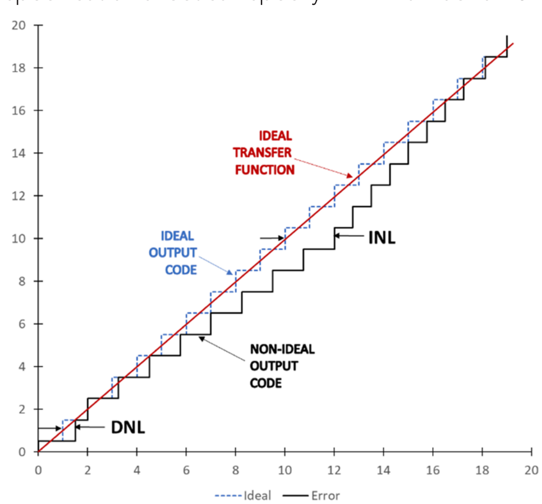

Figure 1: Illustration of DNL and INL

For illustration purposes, assume the DNL is 1.5 LSBs and the INL is 2.5 LSBs such that the accuracy of a 12-bit ADC is shown in Table 3.

Table 3: DNL and INL Examples

ADC Specification	ADC Input Range	12-bit ADC Accuracy (LSB Size)	
		ACS71240LLCTR-010B3	ACS71240LLCTR-050B5
Resolution - DNL	3.3 V	9 mA	30 mA [1]
Accuracy - INL		15 mA	50 mA [1]
Resolution - DNL	5 V	14 mA	46 mA
Accuracy - INL		23 mA	76 mA

[1] Sensor output range exceeds ADC input range

Current Sensor Resolution and Accuracy

There are 3 main sources of error for the current sensor: quiescent voltage output error, sensitivity error, and noise error.

QUIESCENT VOLTAGE OUTPUT ERROR (V_{QVO_E})

The output error at zero input current is usually specified in millivolts from the nominal value over the temperature range and lifetime of the part. This error at zero Amps allied is called Quiescent Voltage Output Error. To convert the output referred V_{QVO_E} to input referred error A_{QVO_E}, divide the V_{QVO_E} in mV by the sensor sensitivity in mV/A, as in Equation 2.

$$A_{QVO\_E}(\mathrm{A}) = \frac{V_{QVO\_E}\,(\mathrm{mV})}{\mathrm{Sens}(\frac{\mathrm{mV}}{\mathrm{A}})}$$

Equation 2: Quiescent Voltage Output Error in mV to A

SENSITIVITY ERROR (E_{SENS})

The output sensitivity error from the expected value when current is applied is given in percent of the input current. To convert to input referred in Amps, use Equation 3.

$$E_{SENS}\ (\mathrm{A}) = \frac{\mathrm{Current\ Sensor\ Input\ (A)} * E_{SENS}\ (\%)}{100}$$

Equation 3: Sensitivity Error in % to A

Note: the sensitivity error usually includes the non-linearity error within it, but the V_{QVO_E} is not included in the linearity. E_{SENS} is the deviation from the ideal transfer function line.

NOISE

Like the ADC LSB, the noise of the current sensor can be thought of as the resolution of the current sensor. Noise is the random error at the output and is dominated by the thermal noise which has a noise amplitude that will vary over time with a Gaussian distribution. Noise is usually specified in two ways.

Total noise (N), over the full bandwidth of the part (or as otherwise noted in the datasheet), can be found in the datasheet in mA_{RMS}, as an input referred specification. Sometimes RMS noise is specified in the datasheet as an output referred spec in mV_{RMS}. In this case, convert to input referred by dividing by Sensitivity, as was done in Equation 2 for the offset. Depending on the application, it may be more appropriate to use peak-to-peak noise than RMS noise. To account for noise amplitude 99.9% of the time, multiply the RMS noise by 6.6 (±3.3 sigma), as is common practice in the industry.

Noise density (N_D) of the thermal noise is noted in the datasheet as an input referred specification and can be used to determine the noise over a different bandwidth than that specified for N, by assuming the noise density is flat over the bandwidth of the part. The low frequency flicker or 1/f with a knee at ~10Hz is insignificant for most system bandwidths and will be ignored in this discussion. To determine the RMS noise over a different bandwidth (BW) than specified in the datasheet for I_N, use Equation 4.

$$I_{ND}(A_{RMS}) = \frac{I_{ND}\left(\mu\frac{A}{\sqrt{Hz}}\right)}{1{,}000{,}000} * \sqrt{BW}(Hz) * \frac{\pi}{2}$$

Equation 4: RMS Noise Using a Given BW

To convert RMS noise to peak-to-peak over a different bandwidth, also multiply by 6.6.

Table 4 illustrates the error sources of the two example parts noted in this article. Note that the resolution of the sensor is independent of the current sensing range, as the noise is dominated by the front-end noise of the hall plates.

Table 4: Error Sources of the ACS71240

Specification	Error Source	ACS71240LLCTR-010B3	ACS71240LLCTR-050B5
Resolution	I_{N_RMS}	53 mA	53 mA
	$I_{N\_peak\_to\_peak}$	350 mA	350 mA
Accuracy	V_{QVO_E} (–25°C to 150°C)	±110 mA	±380 mA
	E_{SENS} (–25°C to 150°C)	±200 mA	±1000 mA

Comparing Sensor and ADC Error Sources

Comparing Table 3 and Table 4, the sensor inaccuracies are generally much larger than the ADC inaccuracy. The RMS noise is similar to the resolution of the ADC. If resolution is critical in the application, then a higher resolution ADC may be desirable.

Figures 2 and 3 illustrate how the current V_{QVO_E} and E_{SENS} show up in the digital domain, assuming an ideal 12-bit ADC. The V_{QVO_E} and E_{SENS} are based on the minimum/maximum specifications from 25°C to 150°C in the datasheet, and are converted to binary code. The maximum number of codes for the worst-case errors are listed in the Table 5.

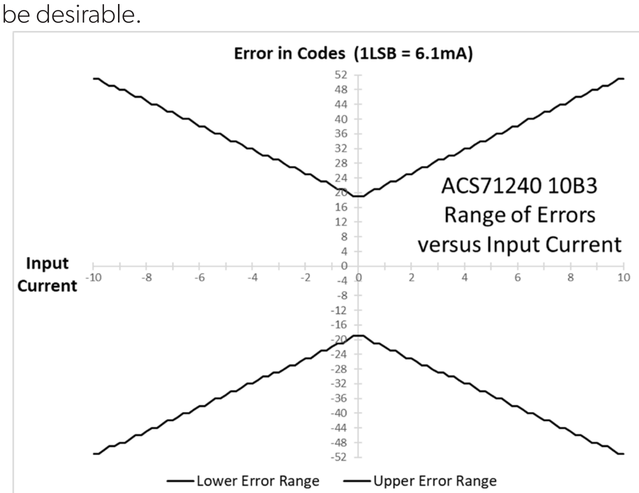

Figure 2: ACS71240-10B3

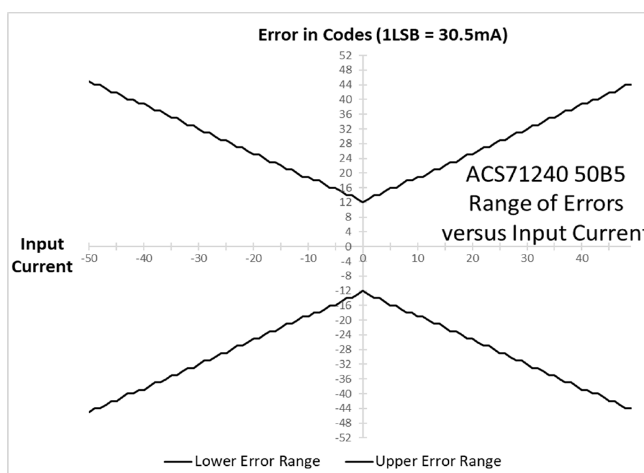

Figure 3: ACS71240-50B5

When the input current is unchanged, noise greater than 1 LSB will show up as changes in the digital code from conversion-to-conversion as seen in Table 5.

Table 5: Maximum Number of Codes for Worst-Case Errors

Error Source	Part Number	
	ACS71240LLCTR-010B3	ACS71240LLCTR-050B5
I_{N_RMS}	8.7 Codes	1.7 Codes
$I_{N\_peak\_to\_peak}$	57.4 Codes	11.5 Codes

CONCLUSION

Referring all errors in Amps will enable easier analysis of the errors in the current sensor and ADC. In many circumstances, using less than the full input range of a 12-Bit ADC will not affect overall system accuracy due to the ADC having higher accuracy than Allegro current sensors. System resolution is unaffected by which current sensor range is chosen and may be limited by the ADC resolution. This application note allows the reader to analyze their own system for resolution and accuracy based on the ADC and current sensor used.

Revision History

Number	Date	Description
–	May 18, 2023	Initial release
1	June 15, 2023	Attribution and tracking updates