CT456 BUSBAR DESIGN GUIDELINES

Optimal Frequency Response and Coupling Factor for TMR Differential Sensing and 300 A Peak Current Range

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INTRODUCTION

The CT456 is a high-bandwidth, low-noise field sensor that uses XtremeSense™ tunnel-magnetoresistance (TMR) technology to enable high-accuracy current measurements for consumer, enterprise, and industrial applications.

CT456 deployment requires a specific busbar pattern—referred to as a snake-shaped current path—to produce a differential magnetic field on a specific axis (the TMR axis of sensitivity). The general busbar shape is shown in Figure 1; three slits or cuts create a snake-like route. When positioned at the center of this busbar design, the CT456 observes a differential flux on the planar surface.

A cross section of the busbar is shown in Figure 2. It illustrates that each TMR sensing element within the CT456 package detects flux in different directions. This occurs because the current in the two channels beneath the sensor flows in opposite directions.

A stray field observed by both TMR elements, however, is uniform and is oriented in the same direction. The differential design of the CT456 thus cancels the stray field.

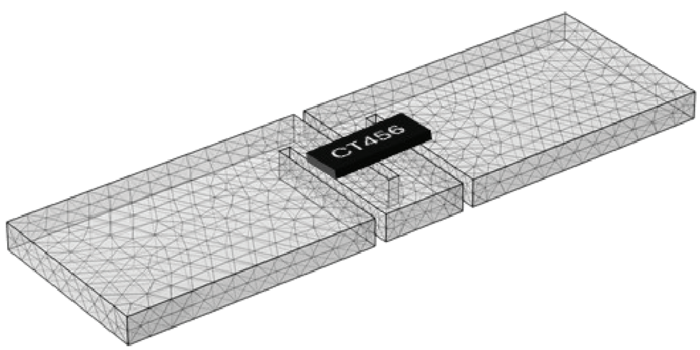

Figure 1: CT456 device atop of a snake-shaped busbar.

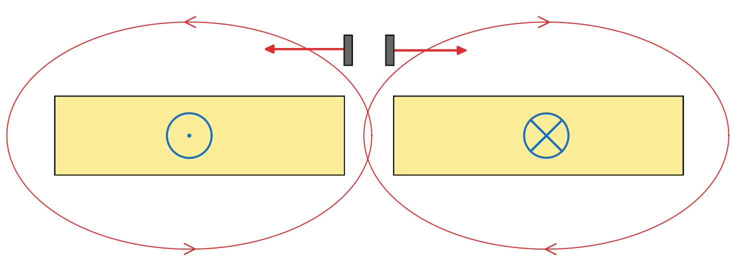

Figure 2: Cross section of the snake-shaped busbar, showing the flux direction and the TMR elements within the CT456 device.

BUSBAR DESIGN CONSIDERATIONS

The design of a busbar that achieves efficient field-current sensing requires consideration for various factors. The application requirements and constraints that affect busbar dimensions are:

- **Current Range (I_{max}):** This is a crucial requirement because it directly impacts the maximum field generated by the system and the temperature rise that results. This is also an essential requirement because it directly affects the maximum and minimum busbar dimensions.
- **AC Performance:** When designing a busbar for measuring high-frequency AC currents, especially those greater than 500 Hz, it is important to address factors that can affect phase shift and sensitivity changes. These issues primarily stem from Eddy currents, which are responsible for the skin effect. The skin effect causes the current to concentrate near the surface of the busbar, altering the shape and strength of the magnetic field at the sensor position. This alteration leads to a phase shift and a change in sensor sensitivity at high frequency.
- **MR Transducer Spacing:** The CT456 is a differential sensor. As such, two TMR transducers are contained within the CT456 device package. To simulate the behavior of a differential sensor, it is important to consider the spacing between the transducers. In the CT456, the spacing between transducers is fixed at 700 µm.

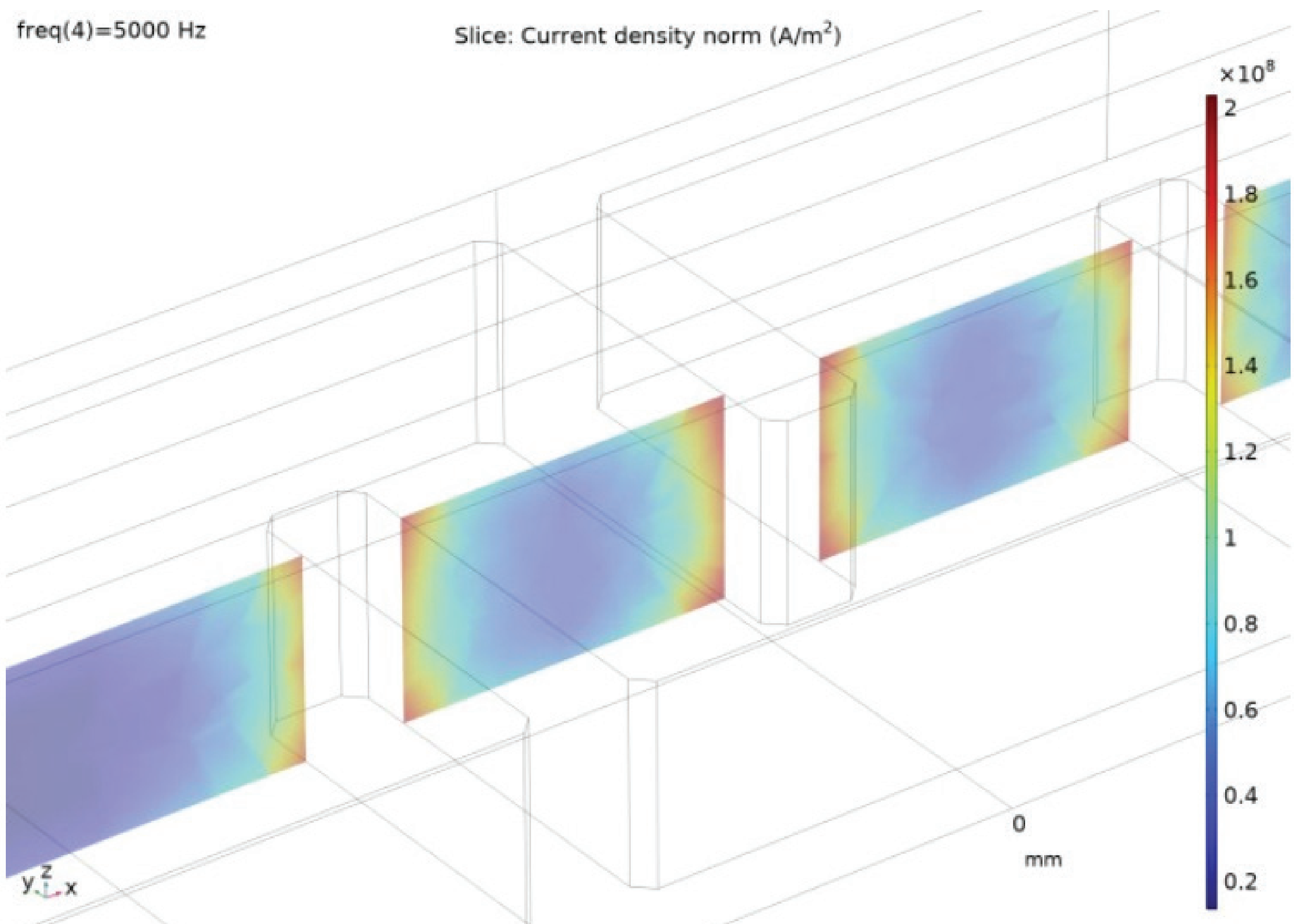

Figure 3: Skin effect on the snake-shaped busbar design.

REFERENCE BUSBAR DESIGN

This application note focuses on the optimized design of a snake-shaped busbar for a maximum current range of 300 A. This current range was selected because it can benefit from the low signal-to-noise ratio and high sensitivity of TMR sensors. This range requires a coupling factor of approximately 20 µT/A.

The recommended dimensions of this busbar are illustrated in Figure 4. The transducers should be placed on the middle of the busbar, at 1 mm air gap. Note that the air gap is the distance between the busbar and the active face of the CT456 package. The TMR elements are located 310 µm below the top surface of the thin-shrink small-outline package (TSSOP), and (generally) 790 µm above the PCB surface (see Figure 5). As a result of this placement, when the top of the package is oriented toward the busbar, the effective air gap between the sensitive elements and the busbar is 1.31 mm for this design.

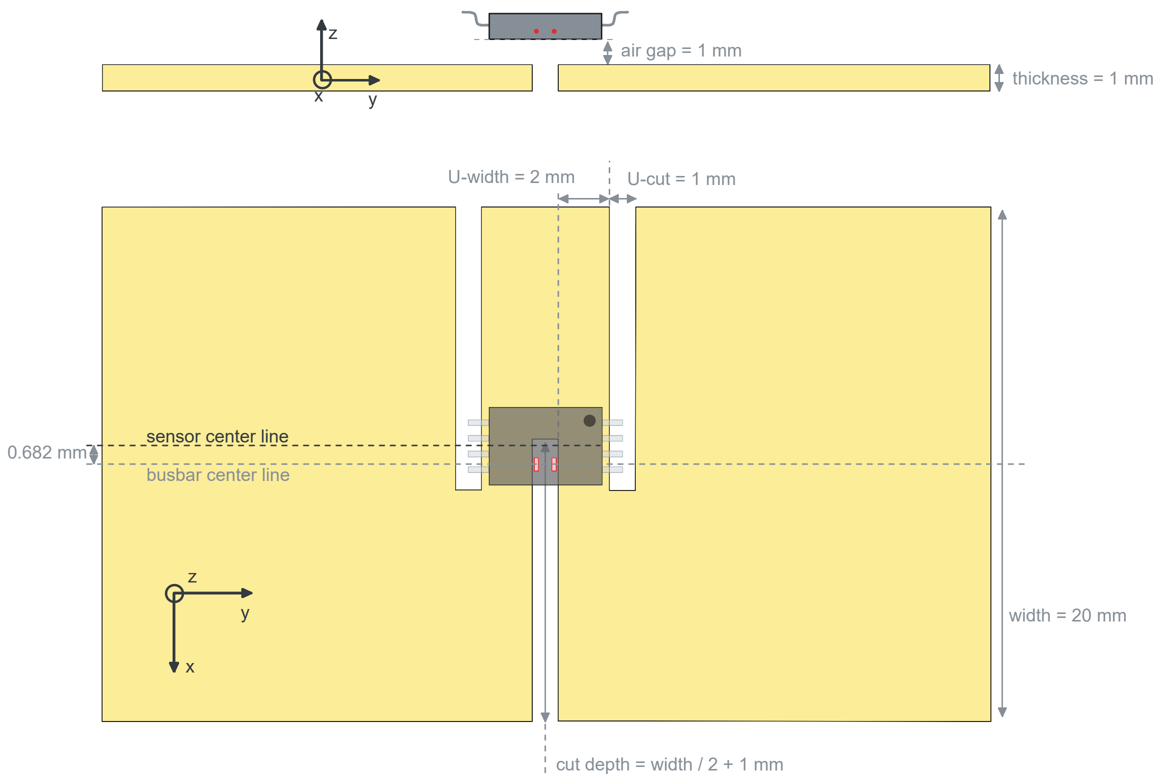

Figure 4: Dimensions of a snake-shaped busbar.

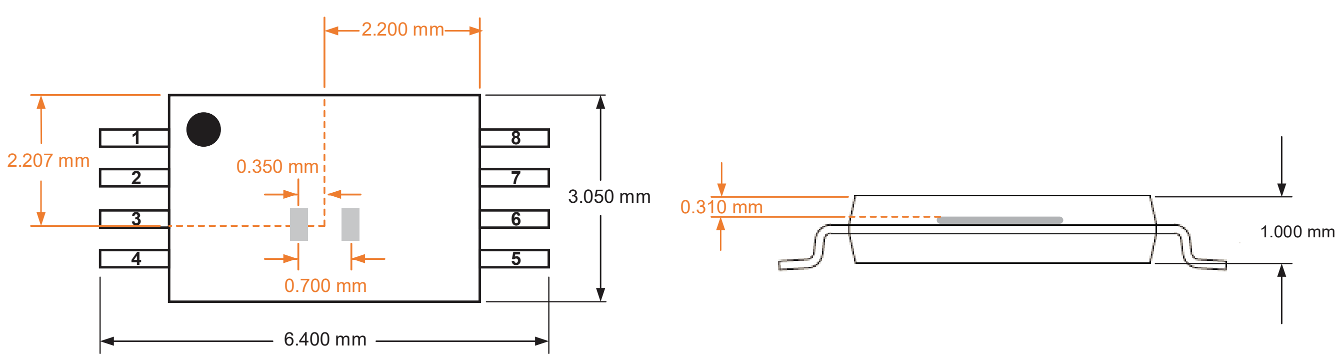

Figure 5: TMR location in the TSSOP package.

DC PERFORMANCE

The busbar illustrated here is 20 mm wide. However, the width can be adapted to fit the application with minimal impact to coupling factor and performance. The coupling factor of the sensor in DC for different busbar widths is illustrated in Table 1. As the table shows, a thicker busbar has a lower coupling factor.

Table 1: DC Coupling Factor of Reference Design

Thickness (mm)	Characteristic	Width (mm)		
		10	20	30
1	Coupling factor (µT/A)	18.2	18.7	18.8
	Current range for 06B5 variant (A)	329	320	318
	Sensitivity (mV/A)	6.1	6.2	6.3
2	Coupling factor (µT/A)	12.5	12.9	13.1
	Current range for 06B5 variant (A)	479	463	459
	Sensitivity (mV/A)	4.2	4.3	4.4
3	Coupling factor (µT/A)	9.3	9.7	9.8
	Current range for 06B5 variant (A)	645	621	612
	Sensitivity (mV/A)	3.1	3.2	3.3

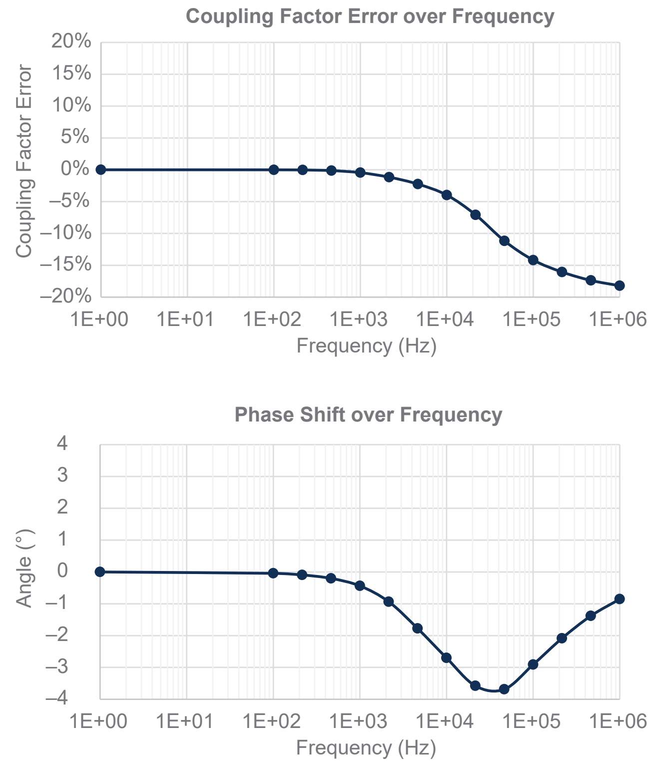

Figure 6: Frequency response.

AC PERFORMANCE

The skin and proximity effects influence current distribution within the busbar. This affects the coupling factor and phase shift between the current in the busbar, as well as the differential field sensed by the CT456. The frequency response of this design is illustrated in Figure 6. The results are for the illustrated geometry (thickness = 1 mm; and width = 20 mm); however, other thicknesses and widths have a similar frequency response.

The geometry of the design has been optimized to deliver optimal performance up to 10 kHz, maintaining a coupling-factor error of less than 4%. Beyond this frequency, the coupling factor decreases. This affects the bandwidth of the final current-sensing solution.

Additionally, the design has been selected to avoid resonance. This ensures that the coupling factor does not exceed the respective DC value at any frequency. This approach avoids overshoots on sharp edges of current.

The frequency response determines how the sensor reacts to current transients. The behavior of differential field that occurs just after a step of current from 0 to 1 A can be simulated. The resulting field is presented on Figure 7.

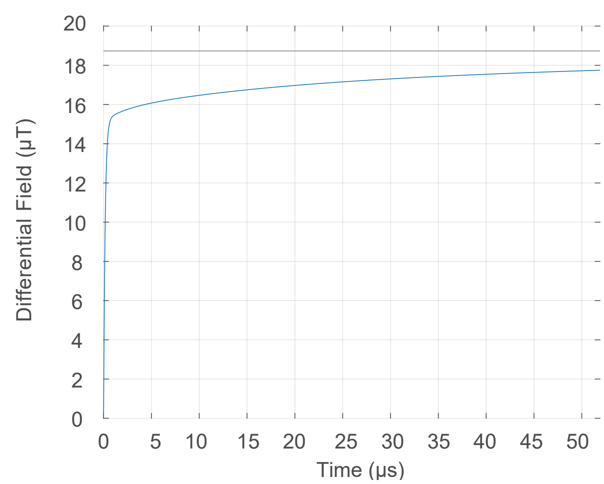

Figure 7: Step response.

SENSITIVITY TO PLACEMENT ERROR

Sensor placement is a critical component to achieve the desired coupling factor. Any displacement or rotation error causes a shift in sensitivity. The error in coupling factor over rectilinear translations is shown in Figure 8. The same error over rotations is shown in Figure 9.

A customer-programmable variant of the CT456 enables simultaneous achievement of relaxed positioning tolerances and high accuracy. End-of-the-line sensor-sensitivity calibration can achieve a very low sensitivity error. For instructions, refer to the software portal [1] on the Allegro MicroSystems website.

The positioning of the sensor relative to the busbar over its lifetime should be controlled carefully. Temperature cycles or vibrations can lead to deformations that affect accuracy.

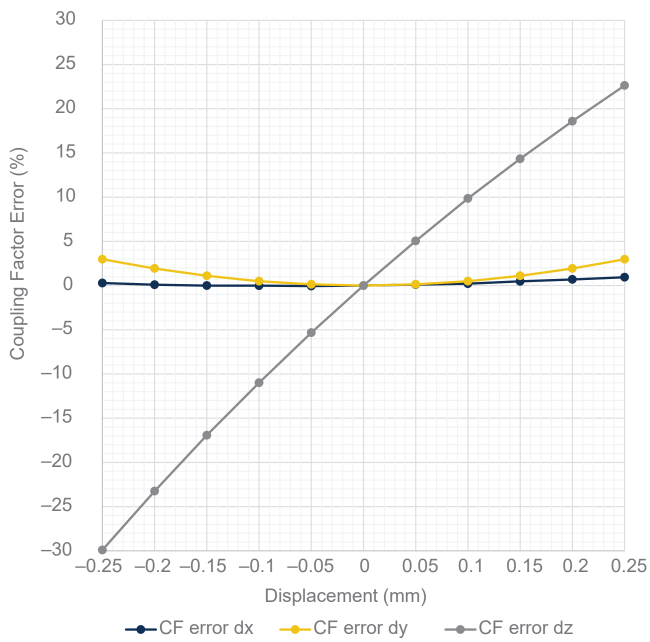

Figure 8: Coupling factor error vs. linear positioning error of the sensor.

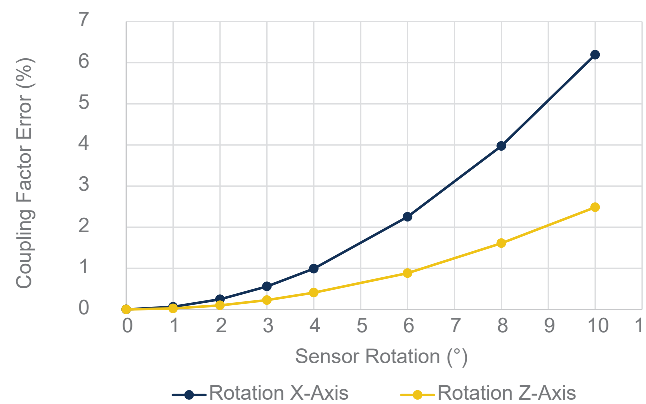

Figure 9: Coupling factor error vs. rotational positioning error of the sensor.

[1] https://registration.allegromicro.com/login

BUSBAR DIMENSION TOLERANCES

For good accuracy, always control busbar dimension tolerances. The coupling factor varies between plus and minus 0.1 mm with variations in thickness, U-cut dimension, and U-width dimension, as shown in Figure 10.

The thickness of the busbar is the most important factor that affects the coupling factor. End-of-the-line calibration of the device is also a solution to eliminate this source of uncertainty.

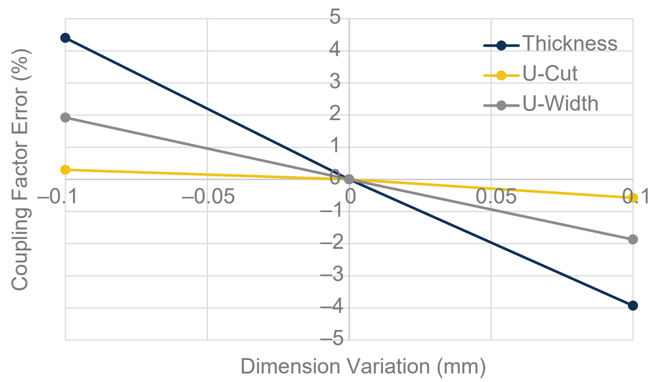

Figure 10: Coupling factor error vs. dimension variations.

SENSITIVITY TO CROSSTALK

The CT456 is a coreless sensor. Therefore, close placement of a conductor that can generate a differential field can affect CT456 accuracy. Because the sensor measures along the Y-axis, it is more immune to crosstalk from adjacent busbars along the X-axis than Hall-effect sensors.

Crosstalk error of the CT456 is presented in Table 2 for two different phase configurations:

- Crosstalk in X refers to the phases being side by side, as shown in Figure 11.
- Crosstalk in Z refers to the phases being on top of each other, as shown in Figure 12.

Table 2: Crosstalk Error

Configuration	Distance		
	1 mm	5 mm	10 mm
Crosstalk in X	0.04%	0.00%	0.00%
Crosstalk in Z	13.21%	0.53%	0.04%

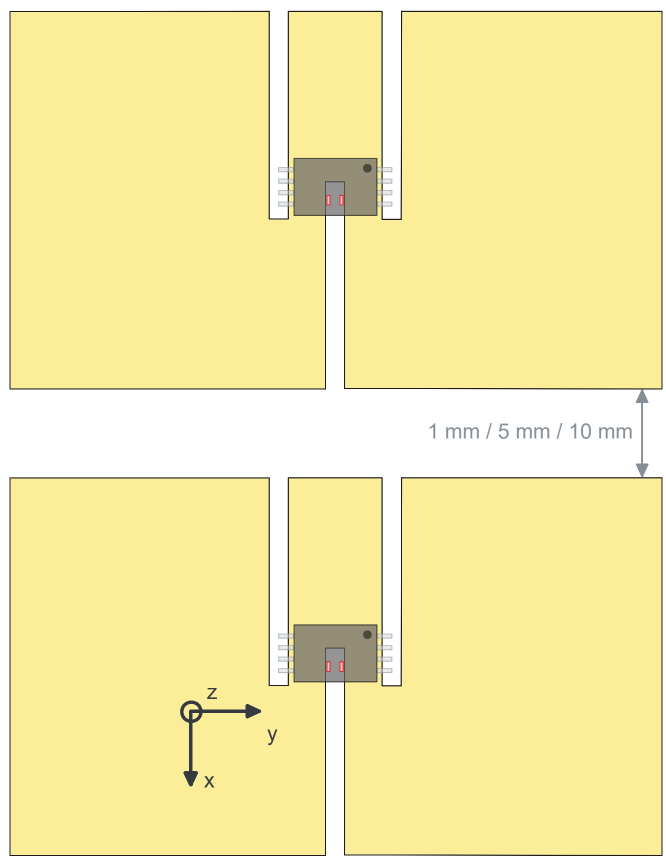

Figure 11: Crosstalk in X.

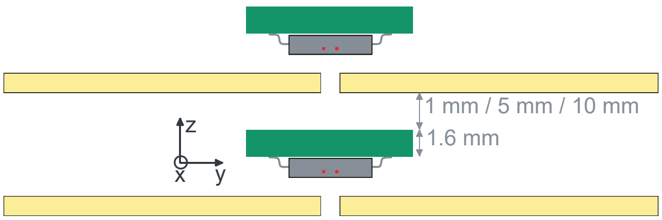

Figure 12: Crosstalk in Z

Vertical conductors (aligned with the Z-axis) that are offset from the center of the sensor are particularly problematic and should be avoided. An example of this undesirable configuration, where a conductor is placed 10 mm from both the center and edge of the busbar, is shown in Figure 13. This undesirable configuration induces a 1.1% error in sensitivity.

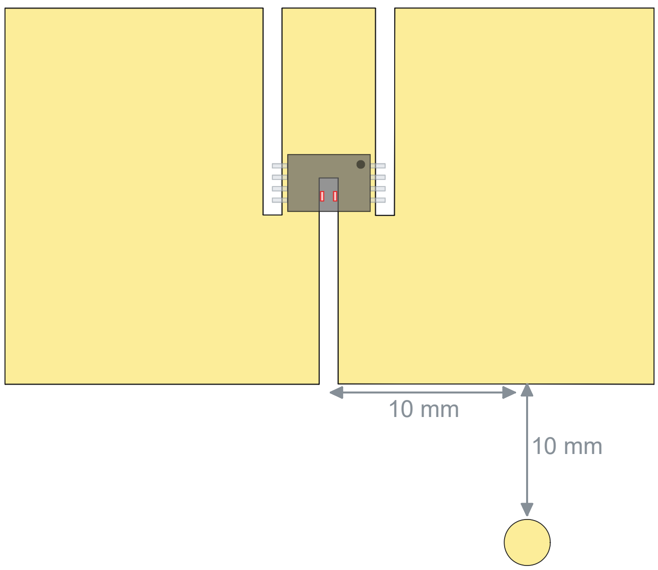

Figure 13: Crosstalk with vertical conductors—Avoid this undesirable configuration.

THERMALS

In comparison to a busbar without any features, the geometry cut into the busbar to generate a differential field increases its resistance. The effect on temperature rise depends closely on the full application and cannot be modeled here. Only the increase in resistance can be described. These values can then be used for thermal simulation of the specific application.

The increase of resistance compared to a busbar without any cut is shown in Figure 14 over all frequencies up to 1 MHz. This factor depends on frequency because of eddy currents—Higher frequencies lead to a lower skin depth and more proximity effect.

Power loss can then be calculated with:

$$P = RI^2$$

For 300 A, the power loss induced by the cuts is 8.5 W in DC, and 10.8 W at 10 kHz.

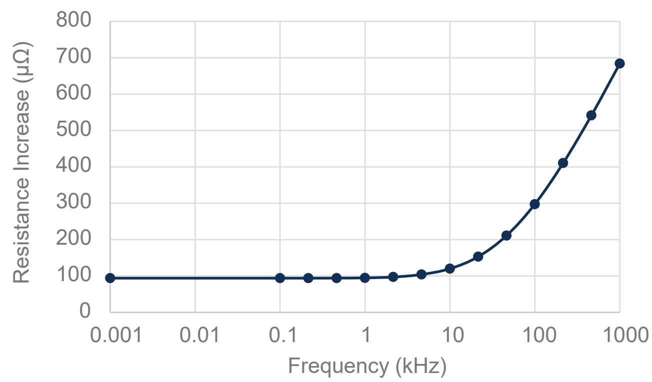

Figure 14: Increase of resistance vs. frequency.

The 1 mm-thick busbar has been tested at 215 A rms (304 A peak). It shows an increase in temperature of 155°C compared to ambient temperature without any cooling. It takes more than 20 minutes to reach that temperature.

With cooling on one side, the temperature on the other side remains significantly lower, only reaching 110°C greater than the ambient temperature.

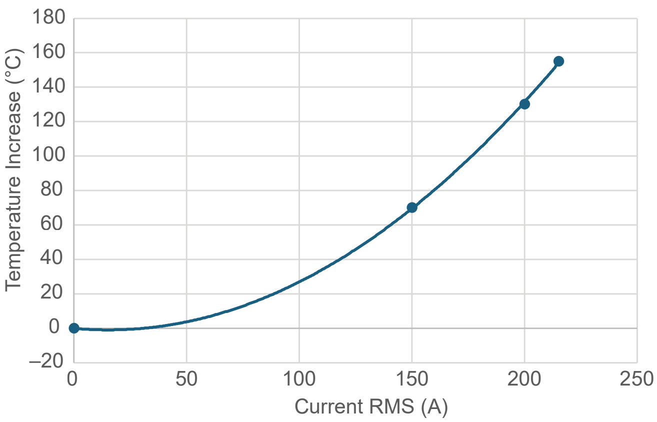

Figure 15: Increase in busbar temperature vs. DC or RMS current after 25 minutes (cooling system not in use).

CONCLUSION

In conclusion, optimization of a busbar design for the CT456 current sensor requires careful consideration of several factors. To generate the differential magnetic field necessary for accurate current measurements while mitigating stray-field interference, a snake-shaped current path is essential. Adherence to the recommended busbar dimensions ensures optimal performance for a 300 A maximum current range, although the width can be adjusted as needed. Busbar thickness must also be considered because it inversely affects the coupling factor. Precise sensor placement is critical, and end-of-the-line calibration, along with careful lifetime positioning management, is advised to minimize placement errors. Furthermore, strategically positioned nearby conductors, especially vertical ones, minimize crosstalk and enhance accuracy. Finally, designers should account for the increased busbar resistance due to the snake-shaped design and should use the provided resistance increase data for accurate thermal simulations within their specific applications.

Revision History

Number	Date	Description
–	March 11, 2025	Initial release