Application Note

TMCS2100-Q1 Design Guidelines

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ABSTRACT

The TMCS2100-Q1 is a Hall-effect magnetic current sensor designed to minimize errors due to crosstalk and mechanical displacement of the sensors with respect to the bus bars. The TMCS2100-Q1 is an ambient magnetic field current sensor that is designed to work in pairs with a secondary device feeding information to a primary device. This document aims to help engineers with their PCB layout, device placement, and mechanical design of their system to minimize errors.

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1 Introduction

The TMCS2100-Q1 Hall-effect current sensor offers industry-leading performance for ambient current sensing applications, but realizing this performance in a system requires careful attention to PCB layout, mechanical design, and device placement. This application note provides practical design guidelines based on electromagnetic simulation to help you minimize measurement errors across your frequency range of interest.

The TMCS2100-Q1 operates as a paired-device system where primary and secondary sensors work together to minimize crosstalk and phase errors. Unlike traditional current sensors, the TMCS2100-Q1 is sensitive to its mechanical position relative to the current-carrying bus bar—a characteristic that demands planning during the design phase.

This document focuses on three critical design areas: bus bar geometry effects, surrounding conductor material interactions, and sensor placement optimization. The analysis covers both DC and AC operating conditions, though the frequency-dependent effects become increasingly important in AC systems operating above a few hundred hertz.

2 Quick-Start Design Checklist

Table 2-1. Quick-Start Design Checklist

Design Parameter	Recommended Value	Impacts
Bus bar to sensor PCB distance	3-11mm	Keeps SNR high while limiting displacement error; farther distances reduce field strength
Sensor placement	Devices placed within 1-2mm of bus bar edge	Maximizes field
PCB copper under sensor	Cut-out (no solid plane)	Copper plane adds significant phase error; cut-out reduces amplitude/phase error over frequency
Conductor proximity	Minimum of 15mm away	Surrounding conductors add phase shifts and amplitude errors; physical separation minimizes this impact
Gain 2 headroom	Characterized Gain 2 < 16128	Increases margin for frequency-compensation circuitry

3 Bus Bar Design

The shape of the bus bar can have an impact on amplitude and phase errors seen at our device. This application note examines two common scenarios of bus bar designs and the general trends to be mindful of when designing the TMCS2100-Q1 into the system. All the scenarios described below were simulated on a 3-phase system.

3.1 Straight Bus Bar

For a straight bus bar it is assumed that the bus bar is flat for at least 50 mm before taking any bends up or down. The following example is based on the TMCS2100EVM. For a straight bus bar with no surrounding metal/conductors it is evident that there is minimal amplitude or phase error over frequency.

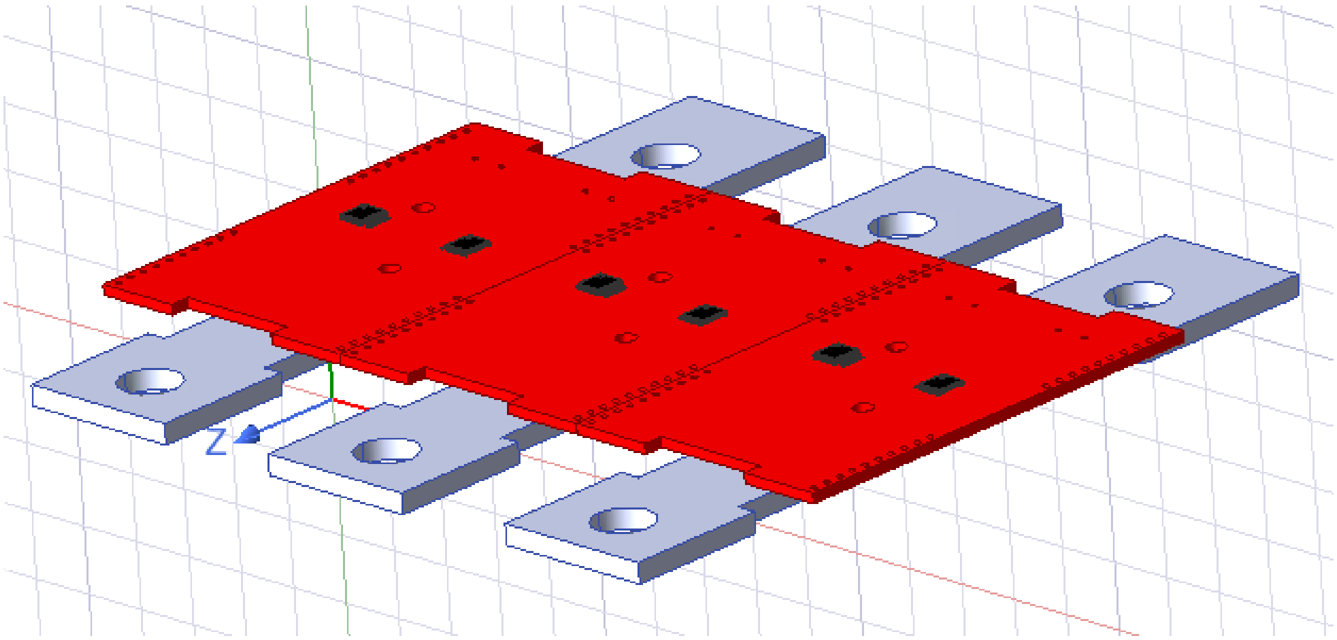

Figure 3-1. Straight Bus Bar Setup

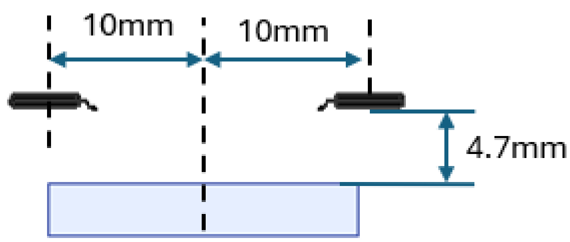

Figure 3-2. Straight Bus Bar Spacing

The error over frequency for a straight bus bar is shown in Figure 3-3. This was done based on our TMCS2100EVMs and the error shown is before frequency compensation. The amplitude and phase errors in this case stay below 1% and 1° respectively.

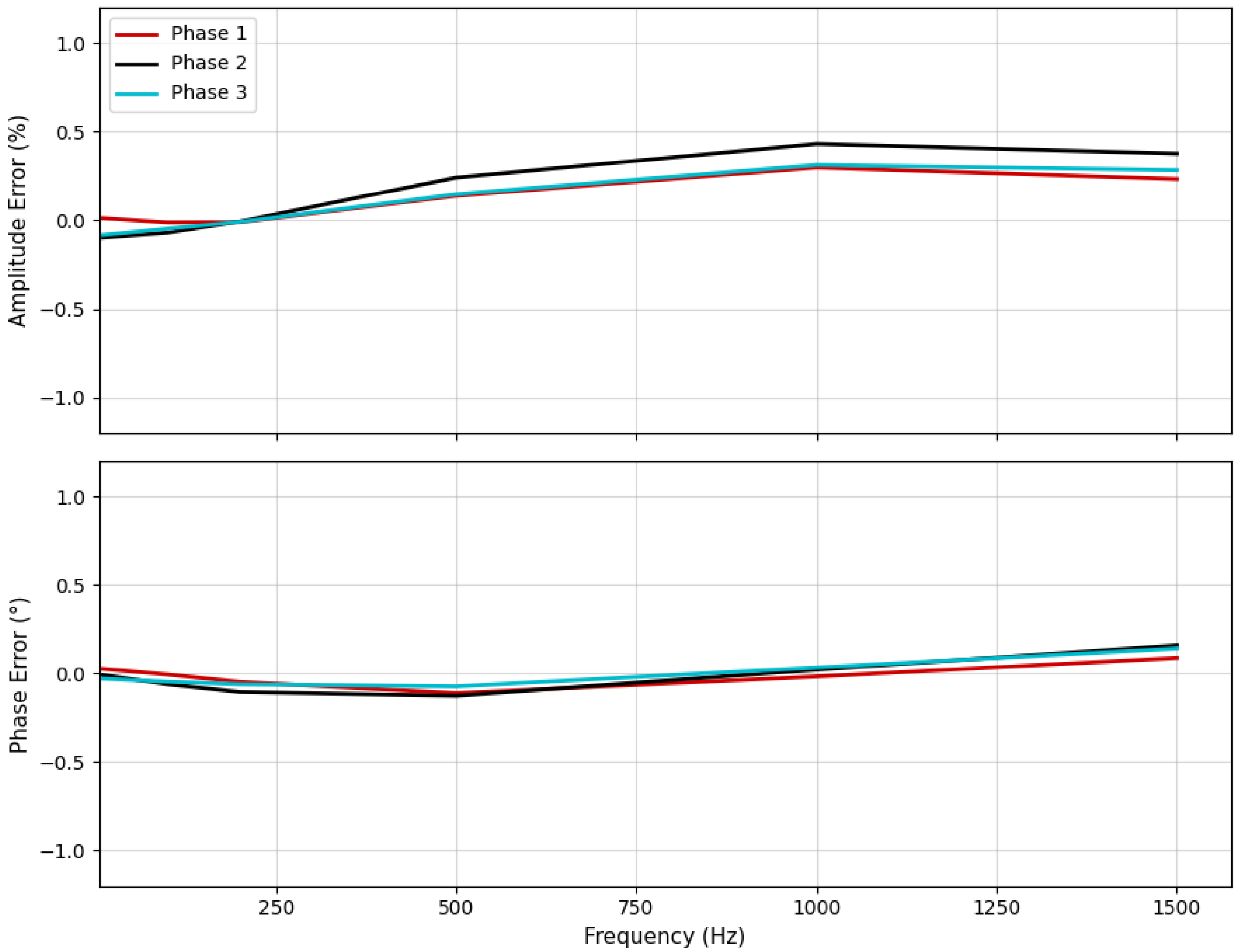

Figure 3-3. Straight Bus Bars Error Over Frequency

The data demonstrates that in an electromagnetically isolated environment (no surrounding conductors), the TMCS2100-Q1 exhibits remarkably stable performance across the 50 Hz to 1500 Hz frequency range tested. This ideal-case behavior establishes a baseline and highlights why real-world systems with surrounding conductors require the additional design considerations detailed in Section 4. The less-than-1% amplitude error and sub-1° phase error seen here represent the best-case; any deviation from this in a system can be directly attributed to environmental factors such as nearby metal planes, PCB copper, or external magnetic field sources.

3.2 Bus Bars with a Bend

Real bus bar designs often have bends that must be accounted for. Figure 3-4 shows an example of a bend in a bus bar with current flowing through it from right to left. There are two black boxes which represent possible sensor placement options. The sensor on the left, S1, is considered *outside of the bend* while the sensor on the right, S2, is considered *inside the bend*.

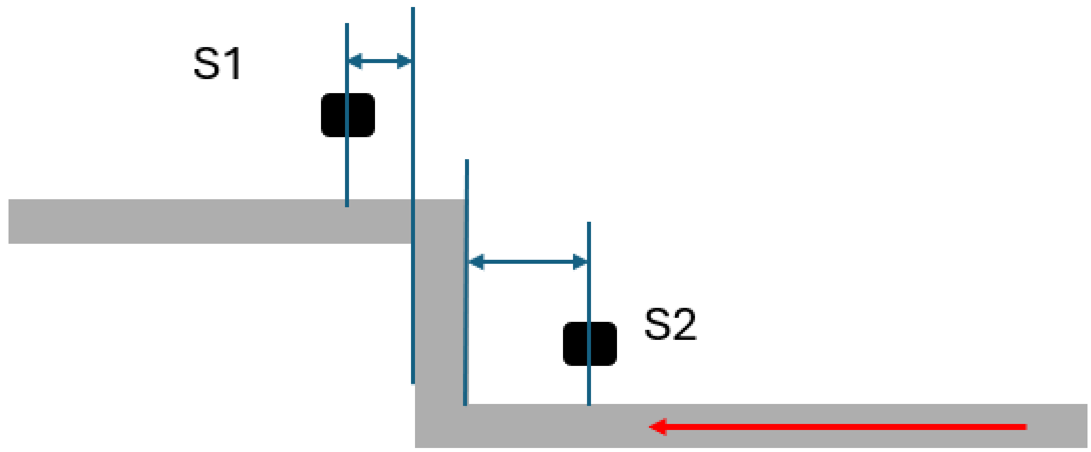

Figure 3-4. Bus Bar with a Bend Setup

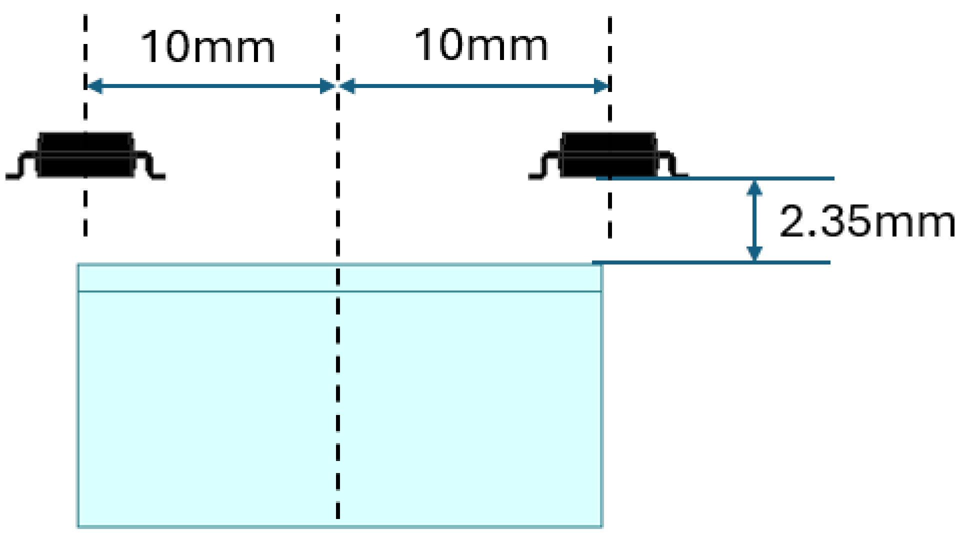

Figure 3-5. Bus Bar with a Bend Spacing

The sensor on the left, S1, in Figure 3-4 is on the outside of the bend and therefore is less impacted by the bus bar bend than the sensor on the right. The sensor on the right, S2, is considered inside of the bend because the field coming from the vertical part of the bus bar will be seen by our sensor as well as the field from the horizontal part of the bus bar. Figure 3-6 shows the amplitude and phase error for these sensors as they are moved away from the bend a certain distance in millimeters.

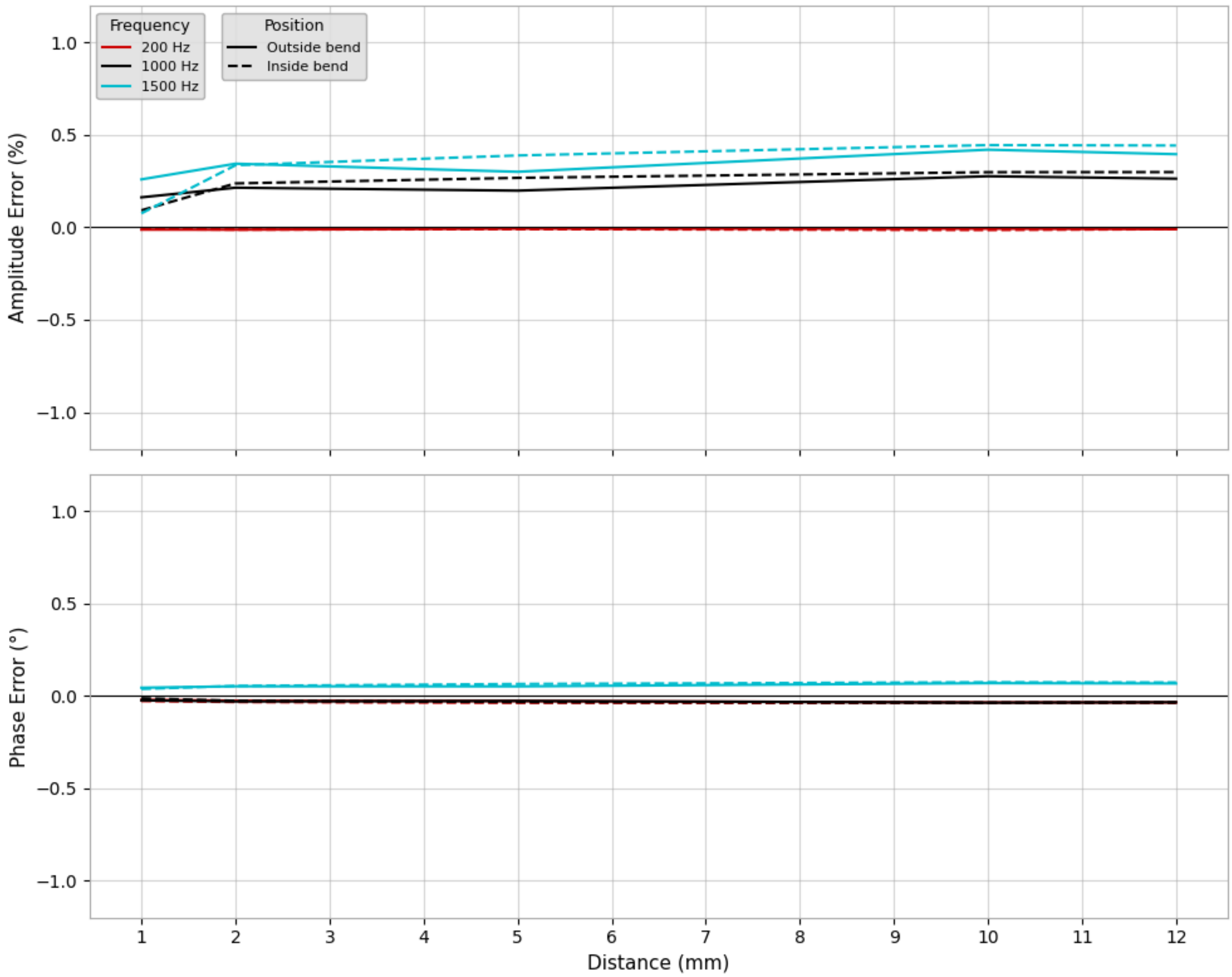

Figure 3-6. Bus Bar with a Bend Error vs Distance from Bend

The solid lines represent errors from the devices outside of the bend and the dashed lines are from the devices inside the bend. There is very minimal difference between the errors from the devices inside the bend and outside of the bend. The location of the sensors matters more as conductors are added to the environment. There is a slight rise in error as the frequency is increased. This is expected due to eddy current effects; there was no frequency compensation applied to the devices in this simulation.

The simulation results reveal a counter-intuitive result—bus bar geometry alone (straight vs. bent configurations) has minimal impact on sensor error when the environment is electromagnetically clean. The sensor placement relative to the bend (inside vs. outside) shows negligible difference, with errors remaining well below 0.5% amplitude error across the 1-12 mm measurement range shown. This finding is significant because it suggests that in preliminary design phases, optimization efforts should be focused on environmental factors (conductor proximity, PCB design) rather than spending excessive effort fine-tuning bus bar geometry. However, this conclusion only holds true for isolated systems—once metal surroundings are introduced in Section 4, the bus bar geometry becomes much more consequential, particularly for sensors positioned inside bends.

4 Surrounding Conductors / Magnetic Materials

When designing in the TMCS2100-Q1 it is important to be mindful of surrounding conductors and magnetic materials as these can introduce offsets and phase shifts. The simulations for the different bus bars mentioned above were repeated with conductors above and below the bus bars and the results are shown here. It should be noted that different materials have different effects based on their relative permeability and conductivity. For example, copper has a higher conductivity than aluminum and will therefore be more impacted by eddy current effects.

The simulations reveal an asymmetry in how conductor placement affects sensor performance. When a conductor exists only below the bus bar, amplitude errors reach 20-25% and phase errors 8-10°—far exceeding the errors when a conductor is present above and below or above only.

4.1 Straight Bus Bar

The straight bus bar simulation was rerun with solid aluminum plates placed above and below the devices. The distance from the top of the bus bar to the edge of the aluminum, X, was swept from 7-24 mm. The ICs are placed in the same location relative to the bus bars as they were in Figure 3-2.

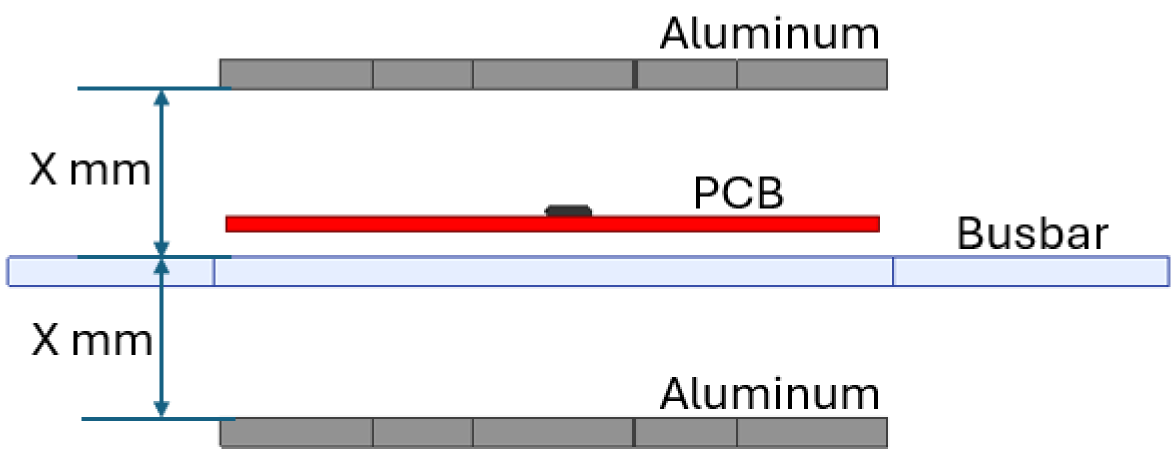

Figure 4-1. Straight Bus Bar Surrounding Metal - Side View

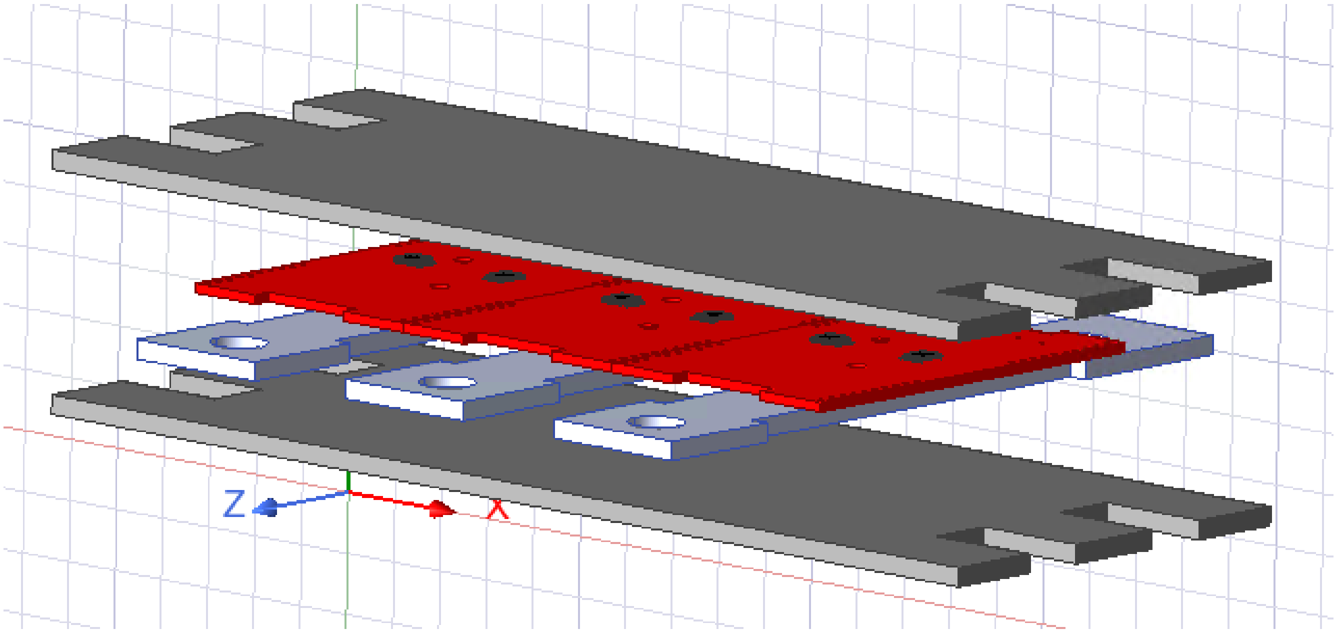

Figure 4-2. Straight Bus Bar Surrounding Metal - 3D

The error vs distance plots, Figure 4-3, for the straight bus bar configuration show that error grows monotonically as a conductor approaches the bus bar. More importantly, the error gradient is steepest at closer distances—the difference in error between 7 mm and 10 mm spacing is substantially larger than the difference between 20 mm and 23 mm spacing. When there is a conductor above and below or only above the bus bar, even when a conductor is only 7-10 mm away, the error impact is minimal. When the conductor is only below the bus bar a larger keep-out area is needed, approximately 15-20 mm.

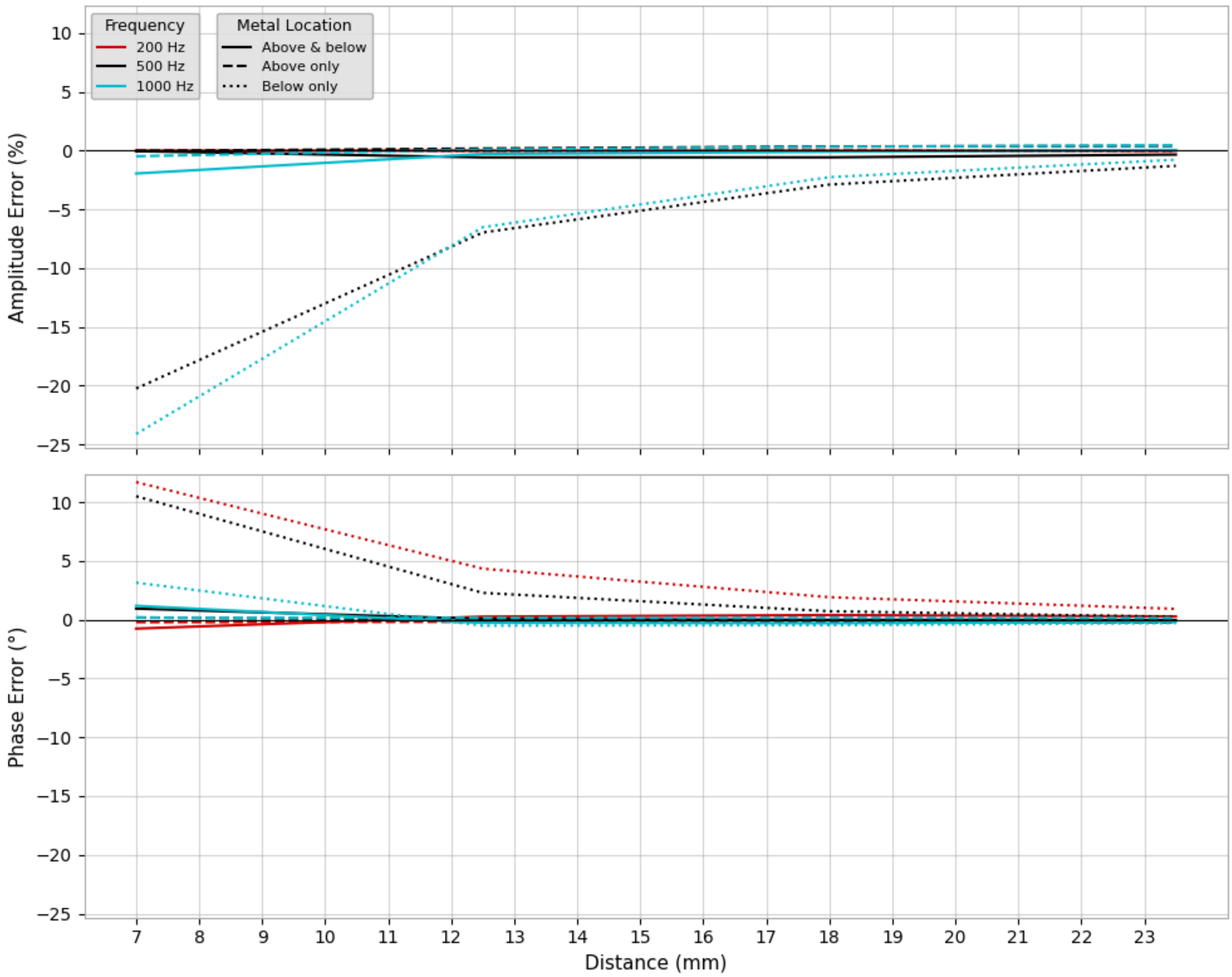

Figure 4-3. Straight Bus Bar Error vs Distance from Surrounding Metal

To get an idea of the impact of surrounding conductors over frequency the error vs frequency is recorded in Figure 4-4 for different distances of the aluminum plate from the bus bar. Significant amplitude and phase errors persist over frequency when there is a conductor only below the bus bars, but this impact decreases as that conductor is moved farther away from the bus bars (red lines the conductor is very close and the blue lines the conductor is much farther).

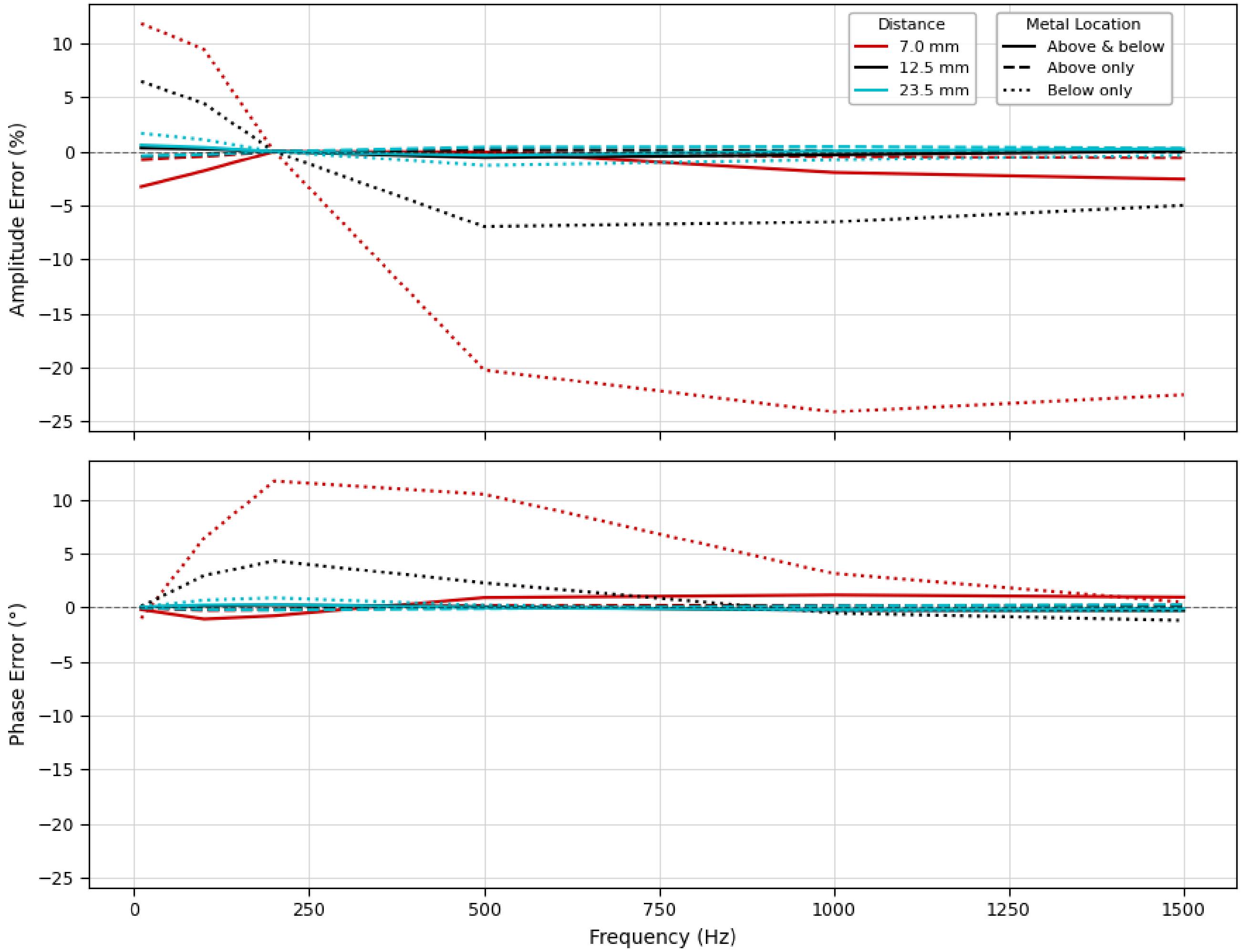

Figure 4-4. Straight Bus Bar Error vs Frequency

4.2 Bus Bars with a Bend

The bent bus bars were evaluated with an aluminum plate placed above and below the bus bar and sensors. The distance to the edge of the aluminum, X, was swept from 1-20 mm away. The top plate was moved relative to the top of the sensor and the bottom plate was moved relative to the bottom of the bus bar. The distance from the bend to the center of the IC, Y, was taken at different values specified in the plots. The ICs are placed in the same location relative to the bus bars as they were in Figure 3-5.

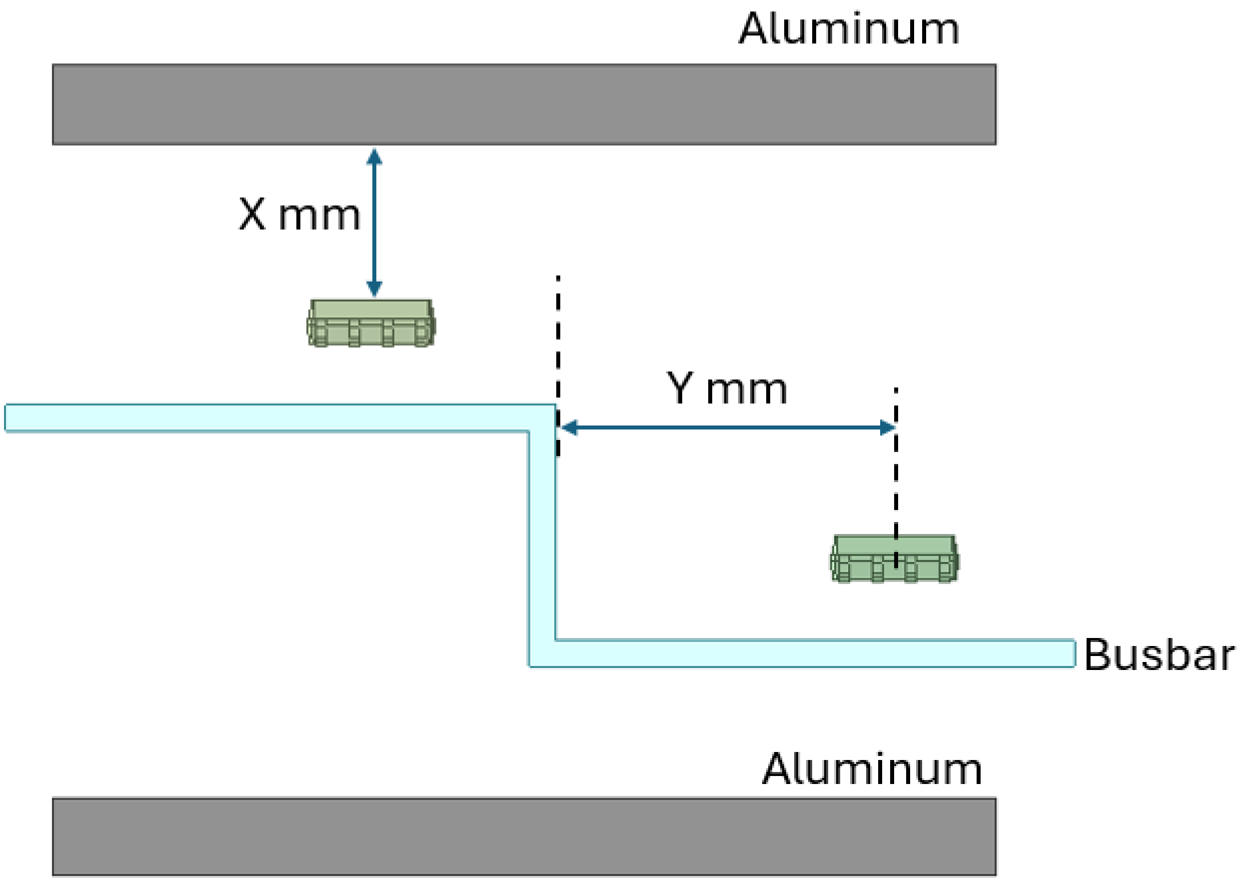

Figure 4-5. Bent Bus Bar with Surrounding Metal - Side View

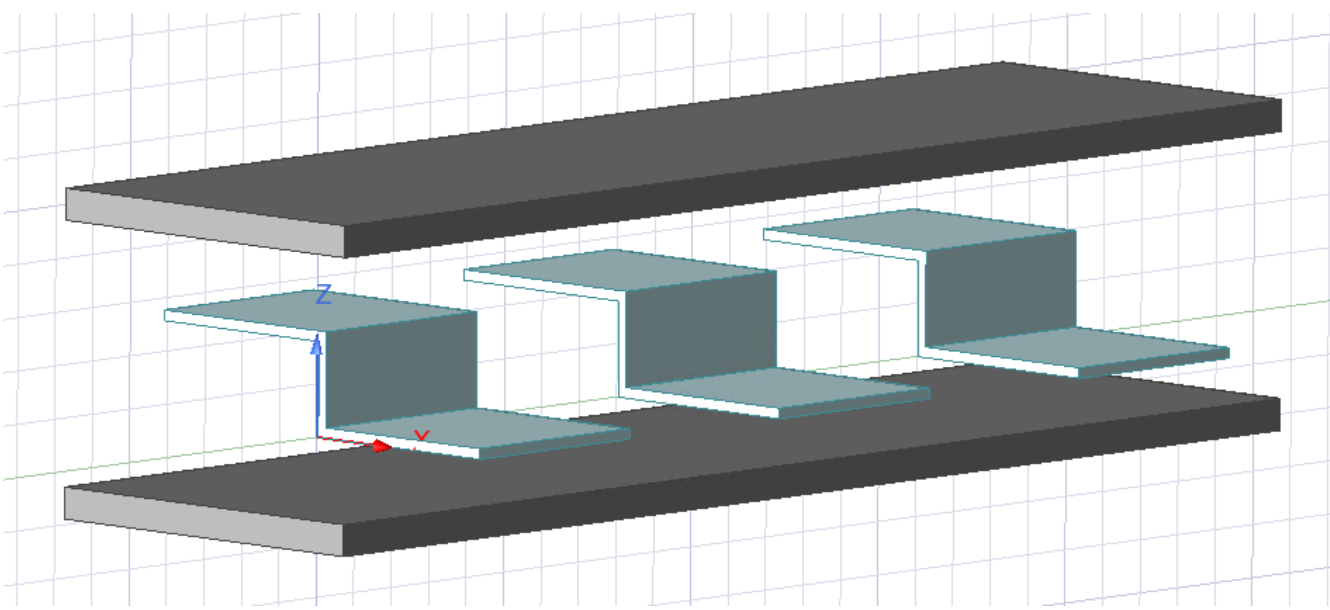

Figure 4-6. Bent Bus Bar with Surrounding Metal - 3D

Figure 4-7 shows the amplitude and phase error vs distance of an aluminum plate from the bus bar (X) as specified in Figure 4-5. The data from the sensors outside the bend is shown on the left and the data from the sensors inside the bend is shown on the right. Each line represents a different distance that the sensor is located from the bend labeled as Y in Figure 4-5 . This data reveals an important practical threshold: in this setup, when aluminum is only below the bus bar and positioned approximately 11 mm away or farther, phase errors drop below 2°. This 11 mm boundary is particularly useful for AC system designs because phase errors cannot be corrected through post-characterization frequency compensation like the amplitude errors are. Sensors positioned inside the bend show slightly higher errors than those outside the bend; there is also a slight improvement as the distance the sensors are from the bend increases (the red lines being closest to the bend and the blue lines being farthest).

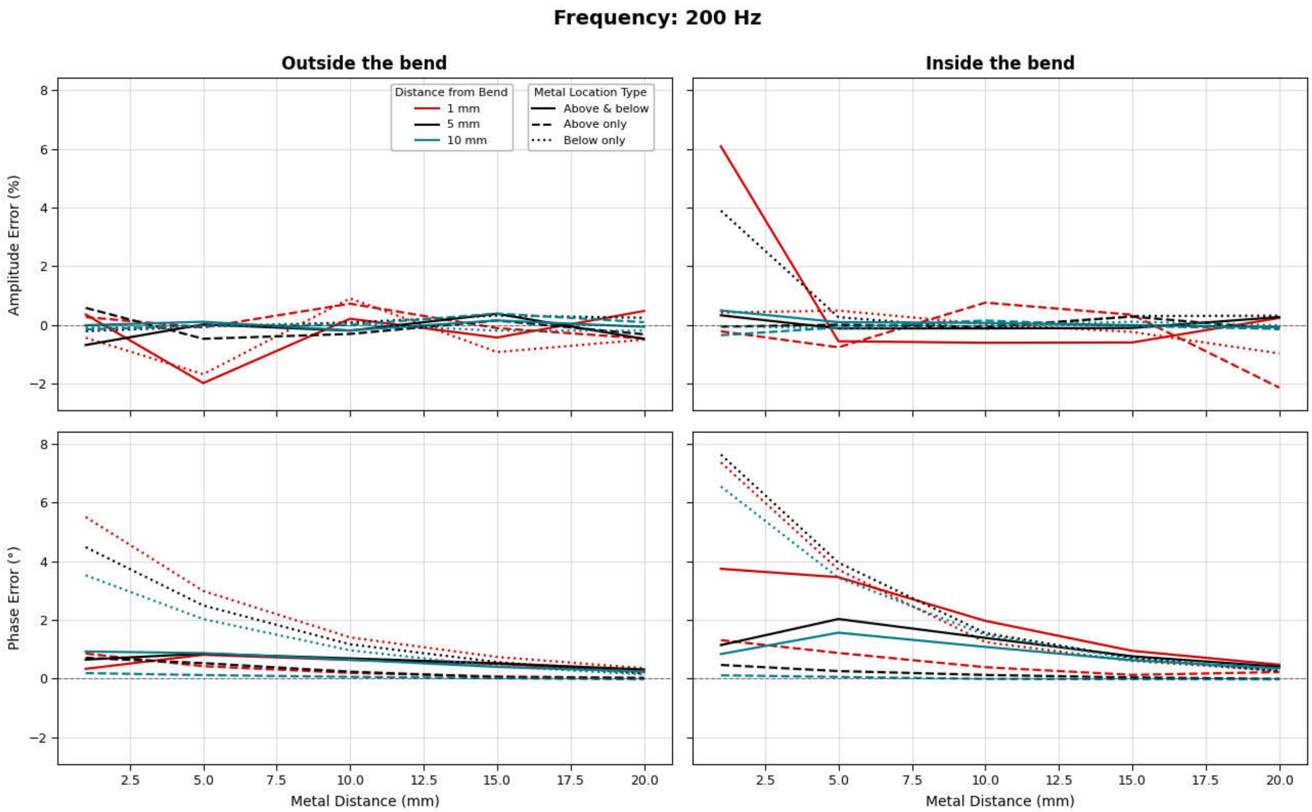

Figure 4-7. Error vs Distance from Surrounding Metal

The frequency-dependent error behavior shown is in Figure 4-8. This data was taken from sensors located 10 mm away from the bend. The data reveals a consistent pattern across both bend positions: conductor placement only below the bus bar (dotted lines) produces worse errors—reaching ±6-8% amplitude and ±3-4° phase error—compared to the other conductor placement options (solid/dashed lines). However, when that lower conductor is positioned **20 mm away or greater**, errors converge with the other configurations, staying below ±2% amplitude and ±2° phase. The ±2% amplitude error is well within the range that is able to be corrected with the frequency compensation procedure. Overall, the errors from the devices outside the bend are about half that of the errors from the devices inside the bend.

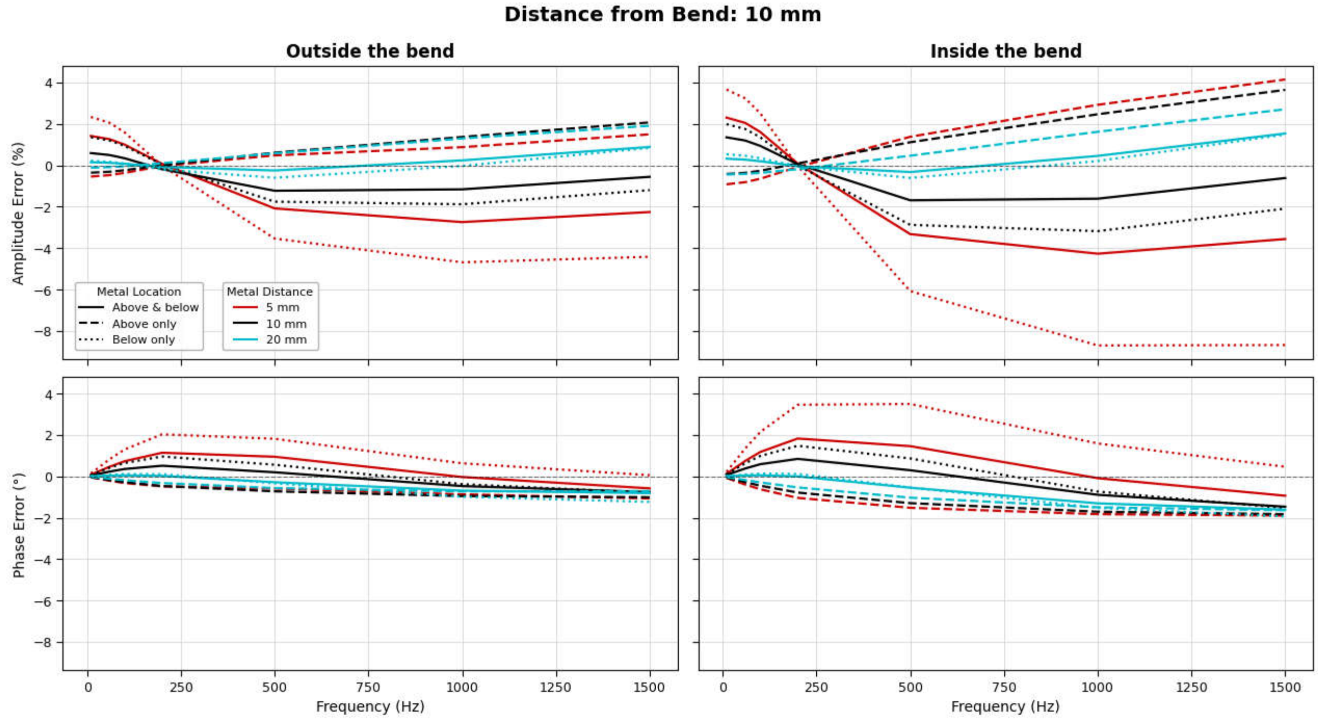

Figure 4-8. Error vs Frequency

4.3 Ambient Fields

Ambient magnetic fields will be reflected on the output of the TMCS2100-Q1. A system level DC offset calibration can be done to account for these fields, but a changing magnetic field will create an offset on the TMCS2100-Q1. Figure 4-9 shows the vertical component of the magnetic field coming from a bus bar. The X axis represents the distance from the edge of the bus bar.

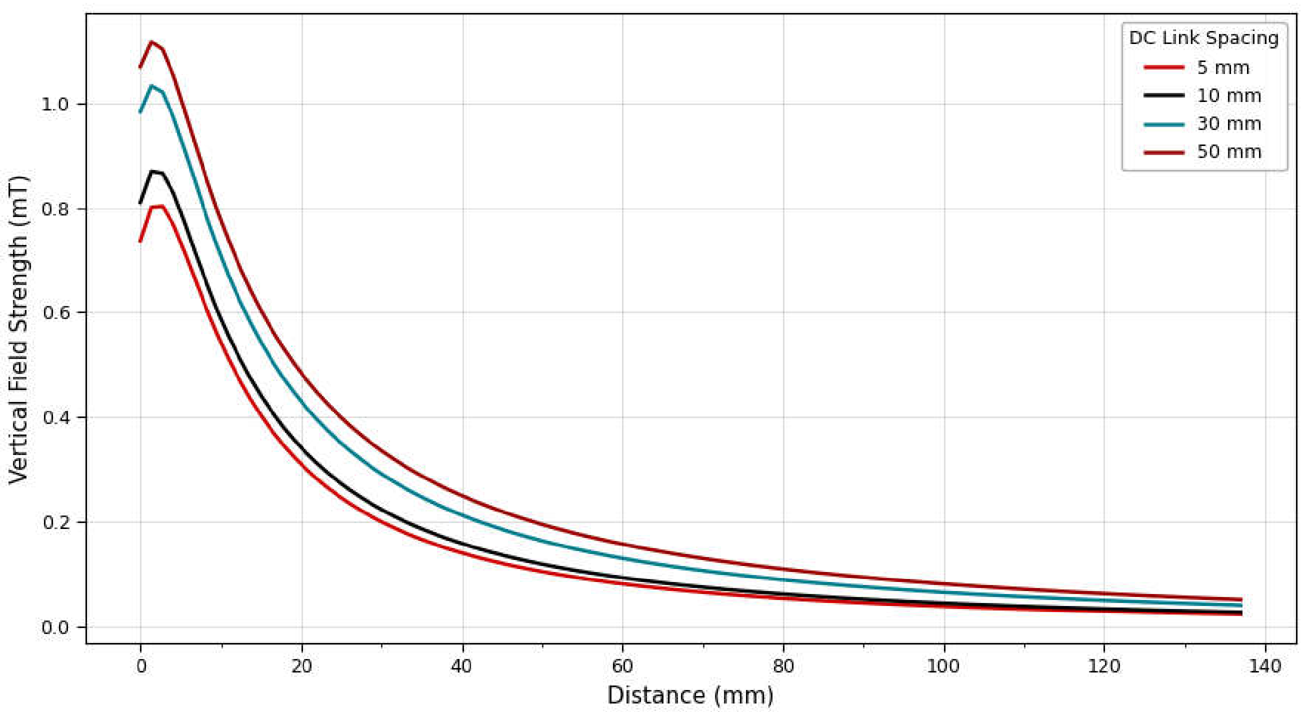

Figure 4-9. Field Strength vs Distance

As expected, the closer the devices are to the ambient field source, the bigger the impact there will be. This specific example is assuming the DC+ and DC- cables of a DC source, such as a DC supply for a three-phase traction inverter, see Figure 4-10. The different line colors in Figure 4-9 represent different spacings between the DC+ and DC- links. The closer together the DC link components are routed, the weaker the magnetic field seen by a device nearby. While a system level DC offset calibration can handle static fields, the changing magnetic field from unbalanced or poorly routed power delivery networks will create time-varying measurement offsets. In systems where maximum accuracy is required, DC link cables should be routed as close together as practical—ideally within 5-10 mm of each other—to minimize the external magnetic field environment.

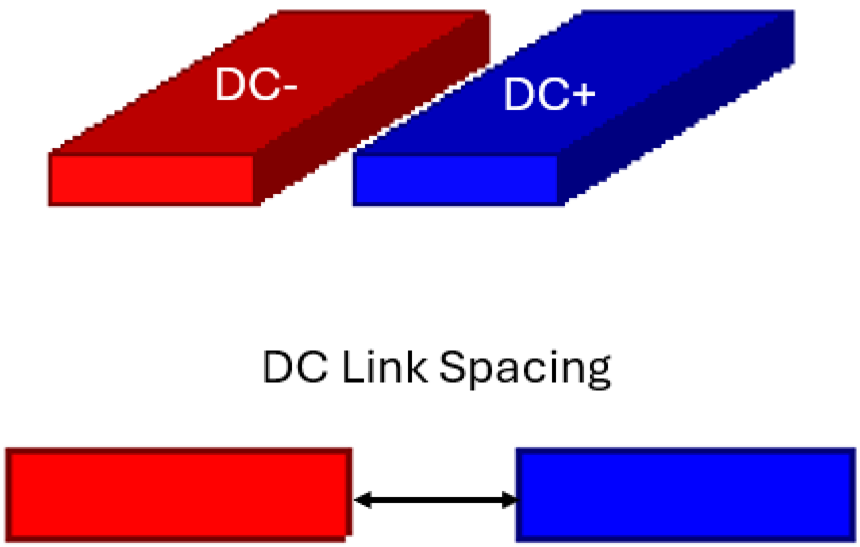

Figure 4-10. DC Bus Bar Setup

5 PCB Cutouts

It is important that any solid copper ground planes on the PCB that contains the TMCS2100-Q1 be removed in the area under the devices. It is recommended that the distance from the outer edge of the IC pins to the edge of the cutout is 2 mm and the distance from the top and bottom edges of the IC to the edge of the cutout is 3 mm. The area between the two devices on a phase should also be cutout. See Figure 5-1.

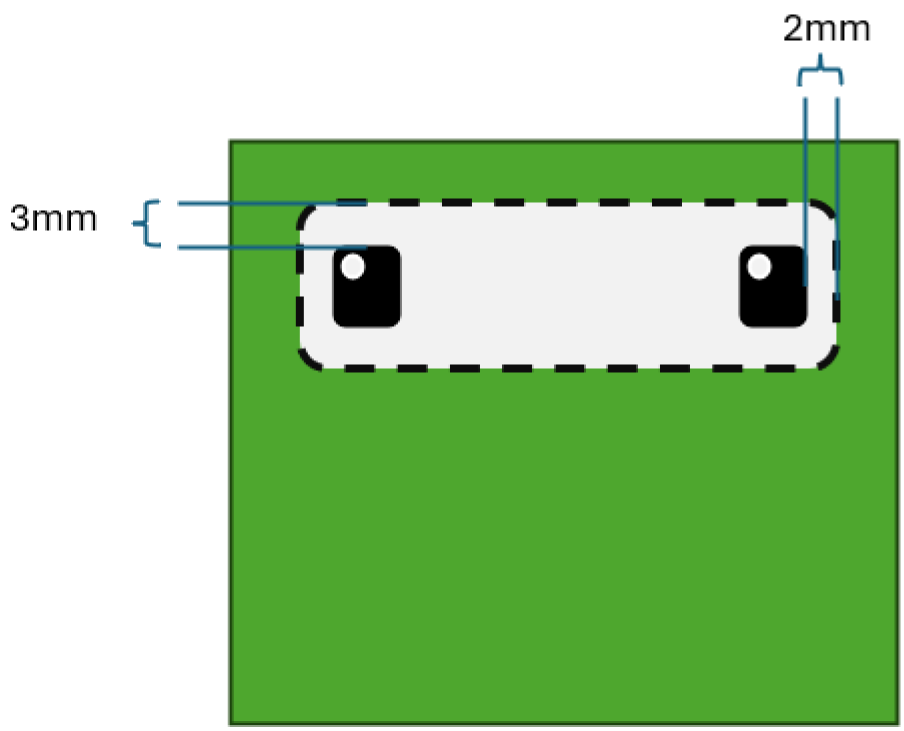

Figure 5-1. PCB Cutout Example

A simulation was done using the same setup as in Section 3.1. There were no surrounding conductors and the PCB was modeled with an without the cutout described in Figure 5-1.

The comparison plot, Figure 5-2, between PCB cutout and no-cutout scenarios shows that solid copper under the sensors create progressive amplitude error growth with frequency, reaching 20% error by 1500 Hz. This is not a small second-order effect—it is one of the dominant error sources in the system. The phase error likewise shows steady degradation. This error grows with frequency, meaning that systems operating at higher frequencies (above 500 Hz) or requiring compensation over wide frequency ranges will suffer severely without PCB cutouts. The dashed line (with cutout) maintains errors below 2% amplitude and 1° phase across the entire frequency range.

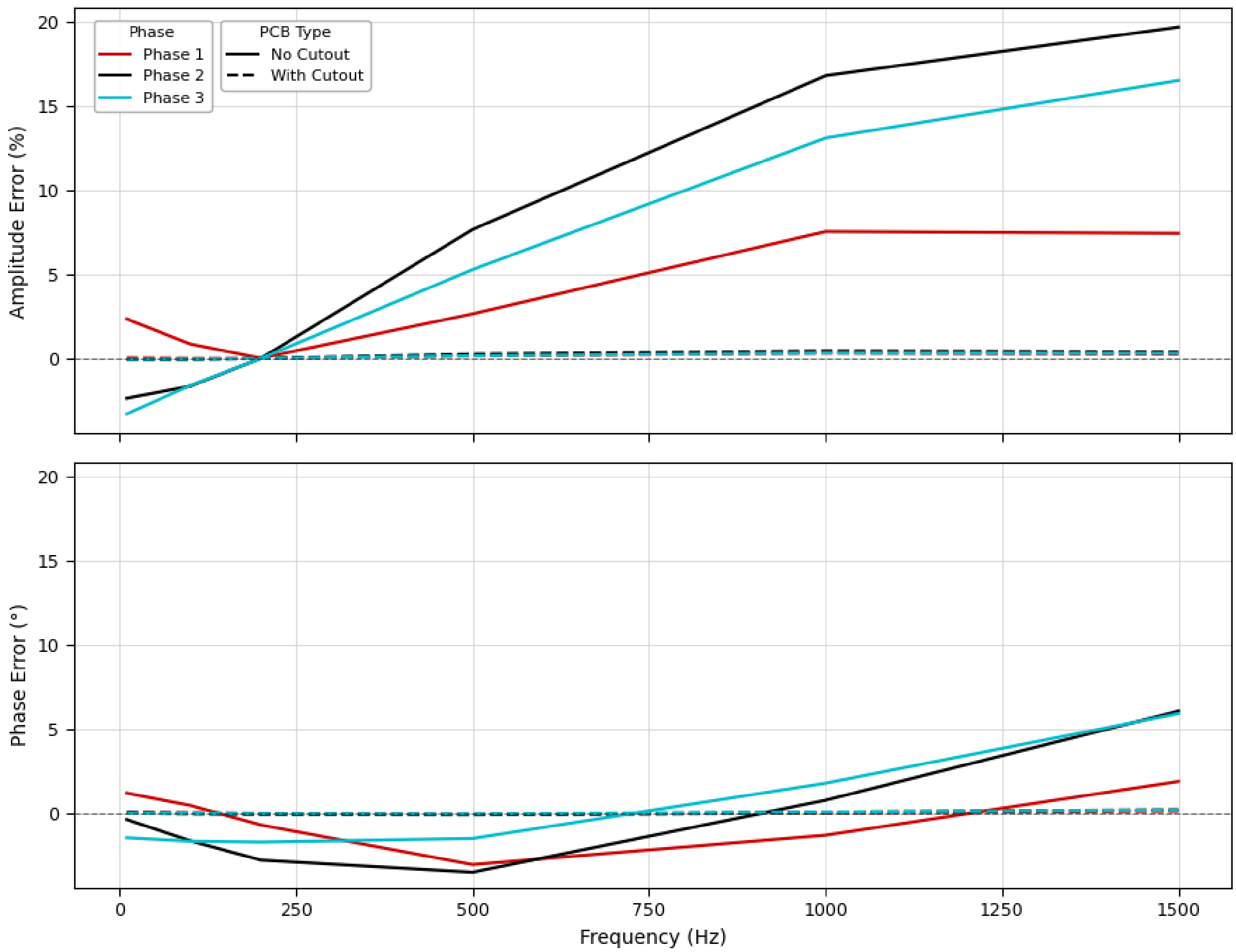

Figure 5-2. PCB Cutout / No-Cutout Error vs Frequency

A detailed layout example can be found in the TMCS2100-Q1 datasheet.

6 Device Placement

The TMCS2100-Q1 is an ambient magnetic field sensor. Device placement on a PCB relative to the current-carrying bus bar is important to ensure that the sensors see a sufficient amount of magnetic field. The placement of the devices also has an impact on displacement error.

6.1 Field Strength

It is important that the TMCS2100-Q1 devices be placed in a location where they will see a sufficient amount of magnetic field for the full-scale range of currents they will be monitoring. The TMCS2100_DC_SIM_TOOL allows users to quickly simulate a simple 2D, DC system. The user can vary the device spacing as well as the distance from the bus bars to the device PCB and calculate displacement errors. This tool also serves to help the user determine which device gain variant, A1, A2, or A3, will be needed for their system. It is discussed in more detail in Section 7.1.

6.1.1 Distance from Bus Bar to Sensor

It is recommended that the distance from the bus bar to the sensor PCB remain between 3-11 mm. However, there are factors that can allow this distance to be pushed farther (at the cost of SNR). The DC simulation tool is a good starting point to test design feasibility for the given device gain variant and full-scale range selected by the user. It is recommended that the user selects a device spacing that puts the devices 1-2 mm away from the edge of the bus bar.

The plots in this section are meant to describe a general trend, rather than strict design rules. The full-scale range as well as device gain variants and bus bar geometry play a key role in determining what makes a sensor placement location feasible. The plots in this section were all created using the A3 device variant. If the A1 device variant was chosen there would be a smaller range of PCB distances that allow us to converge on a solution. This will be discussed in more detail in Section 6.1.3.

Physics tells us that in order to minimize displacement error the sensors need to be farther away from the field source because magnetic fields decay inversely with distance. Therefore, being farther away from the source places the sensors in an area where the magnetic field is decaying slower. However, placing the sensors infinitely far away from the source they are trying to measure will cause a degradation in the signal to noise ratio (SNR). Figure 6-1 shows the noise error (upper plot) and amplitude error (lower plot) vs distance from the bus bar to the sensor PCB . Different device spacings were chosen and plotted and the bus bar in this setup is 19 mm wide and 3 mm thick.

As shown in the top section of Figure 6-1, the further the sensor PCB is from the source conductor, the higher the noise error (lower SNR). However, SNR is only one piece of the puzzle. Note the Y-axis scale of the two plots are not the same! The noise error plot shows an abnormal spike down on the red line (4 mm device spacing) at the 13 mm mark. This aligns with an error spike shown in the lower plot indicating there is not a sufficiently strong magnetic field at that location for the devices to properly characterize.

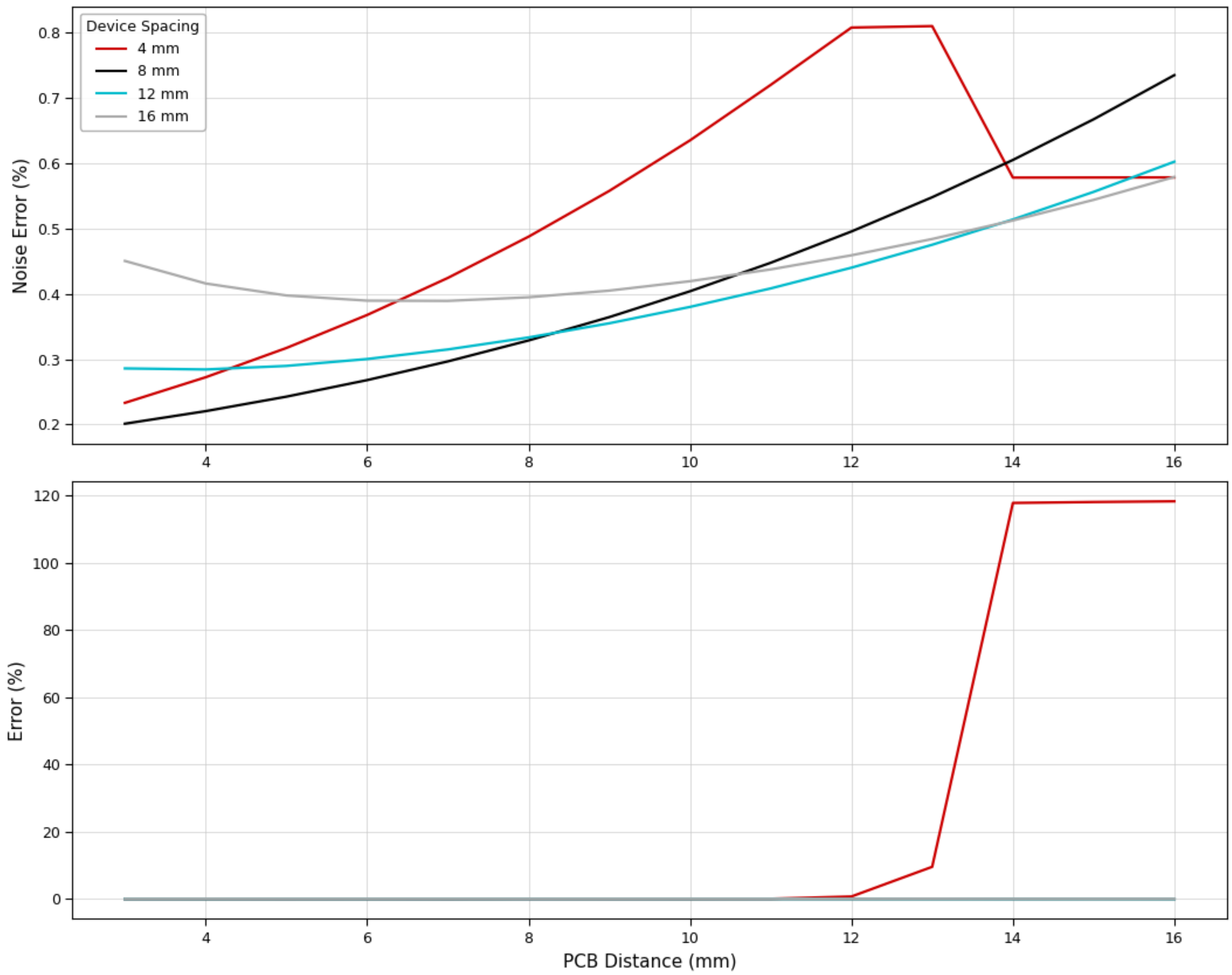

Figure 6-1. Errors vs Distance from PCB

6.1.2 Sensor-to-Sensor Spacing

If the distance from the sensor PCB to the bus bar is fixed the user still has the ability to vary the placement of the sensors relative to the center of the bus bar and one another. Figure 6-2 shows the errors vs the device spacing relative to the center of the bus bar. Each line represents a different distance from the bus bar to the sensor PCB.

The plots reveal that, as expected, if the PCB distance increases the noise error also increases regardless of device spacing. The amplitude errors in the lower half of the graph show that a device spacing less than 4 mm and 5 mm provide insufficient field strength for the devices to characterize at a PCB distance of 10 mm and 12 mm, respectively.

For the PCB distance of 2 mm (red line in the top half of the plot) as the device spacing increases beyond 10 mm the noise error begins to rise. At these farther spacings the sensors move to a region of mainly vertical field which means they see less signal due to the lack of field seen by the horizontal sensor. When the PCB is farther from the bus bar moving the device spacing to these farther distances (> 12 mm) is not as much of an issue because the sensors will still be seeing field in both the horizontal and vertical directions.

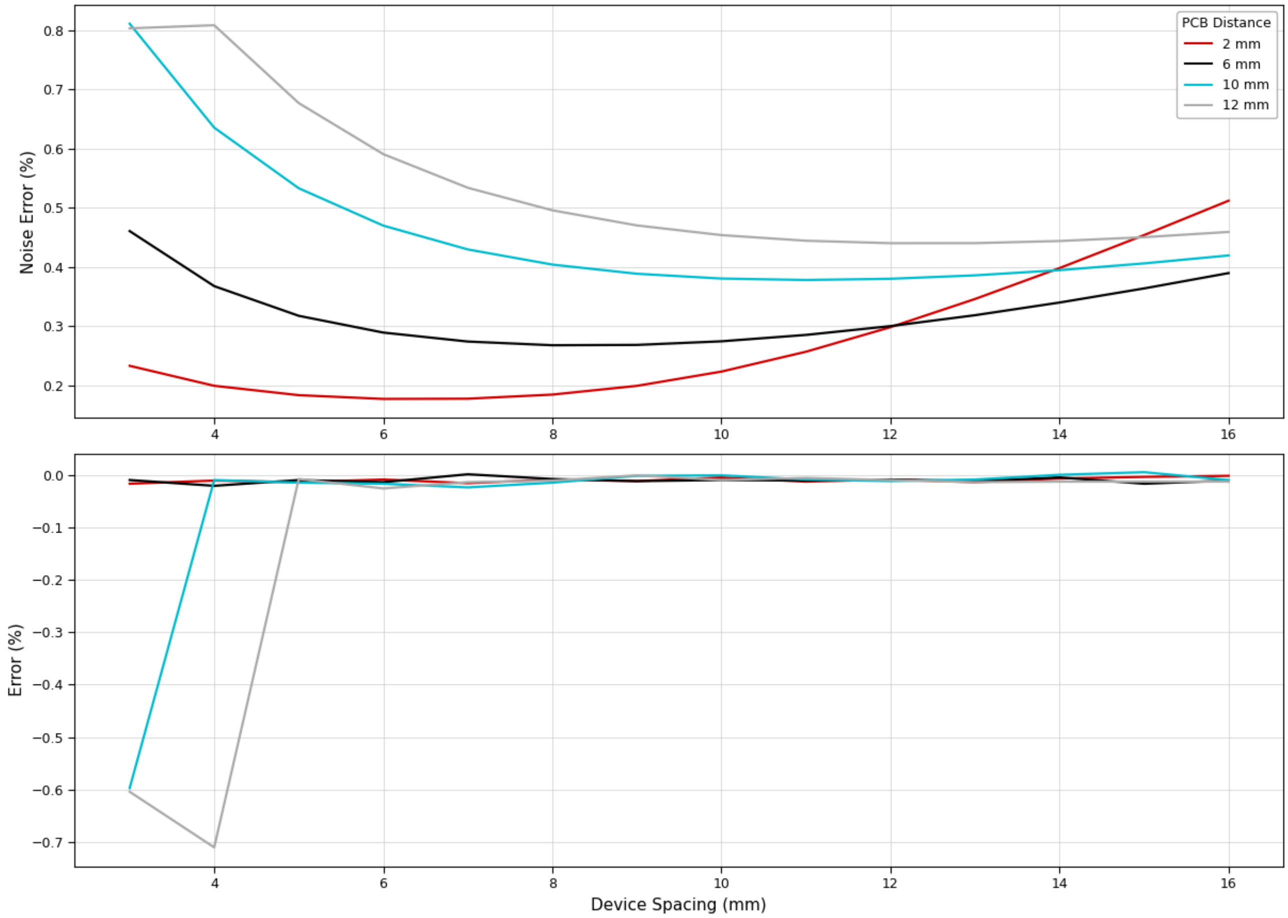

Figure 6-2. Errors vs Device Spacing

6.1.3 Full-Scale Range and Device Gain Variants

6.1.3.1 Device Gain Variants

The device gain variant chosen, A1, A2, or A3 directly affects the feasible device placement locations. Figure 6-3 and Figure 6-4 aim to provide some intuition on the benefits of when to use each device variant.

In Figure 6-3 the device spacing is fixed at 9.5 mm from the center of the bus bar which represents the devices being aligned with the outer edges of the bus bar. The full-scale range was set at 1200A. The distance from the bus bar to sensor PCB was swept and the results shown for each device gain variant.

For the given configuration the A1 device gain variant is only feasible for a PCB distance up to 3 mm. The A2 variant is feasible up to 10 mm and the A3 variant up to 16 mm. Beyond these distances the sensors do not have enough gain to scale the magnetic field to meet the full-scale range specified.

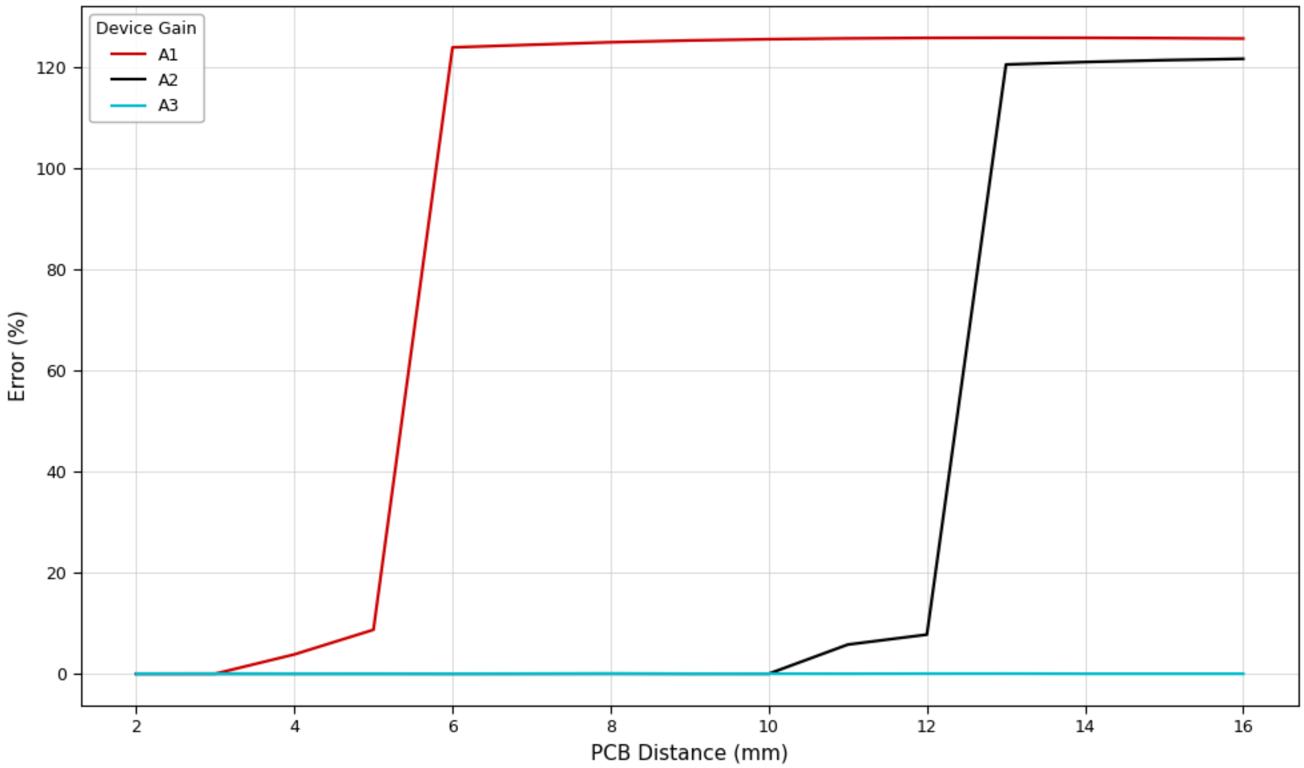

Figure 6-3. Error vs Distance from PCB (different device gains)

Figure 6-4 shows the error vs device spacing for a fixed bus bar to sensor PCB distance of 4 mm. Once again A1 has the most limited range of device spacing whereas the A2 and A3 devices show reasonable error across the whole device spacing range tested.

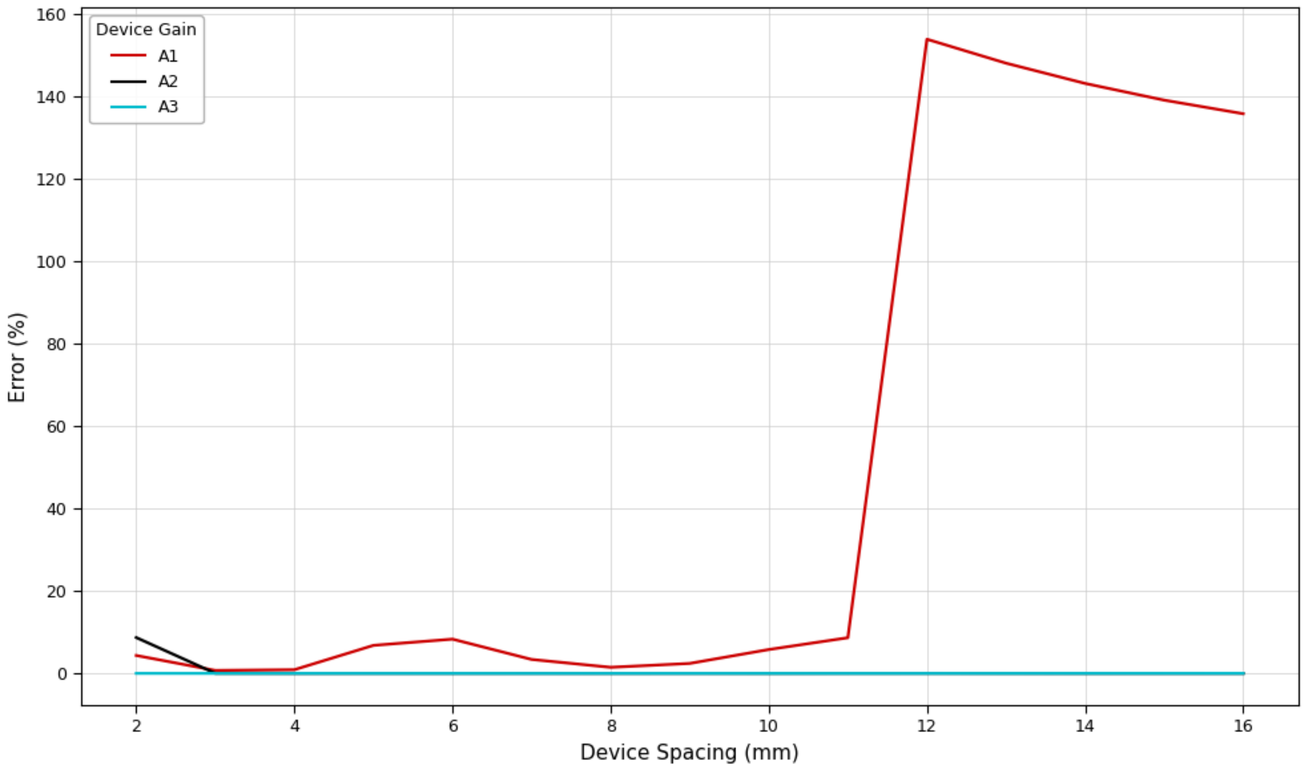

Figure 6-4. Error vs Device Spacing (different device gains)

6.1.3.2 Full-Scale Range

Just as device gain variants constrain where a device can be placed, the full-scale range set by the user also impacts device placement. The A3 variant was used and four different full-scale range (FSR) values chosen: 300 A, 600 A, 1200 A, and 2000 A. Figure 6-5 shows the error vs bus bar to sensor PCB distance for each of the chosen FSRs. The device spacing was fixed at 9.5 mm which corresponds to the edge of the bus bar; this is the same as the setup in Section 6.1.3.1.

For this setup, the FSR plots reveal that low full-scale ranges (300 A) create a tight window for acceptable PCB distances (roughly 3-4 mm), while high FSR values (2000 A) shift this window farther away but introduce a different constraint—the minimum distance from the bus bar cannot be too close, or saturation error emerges. This creates a design optimization problem: the FSR choice must be compatible with the mechanical mounting distance. If the system requires 2000 A full-scale but the thermal or space constraints force the PCB too close to the bus bar, there could be significant error. In such cases, revise either the FSR (by accepting lower full-scale current measurement), choose a lower device gain variant, or modify the mechanical design (by finding additional PCB clearance).

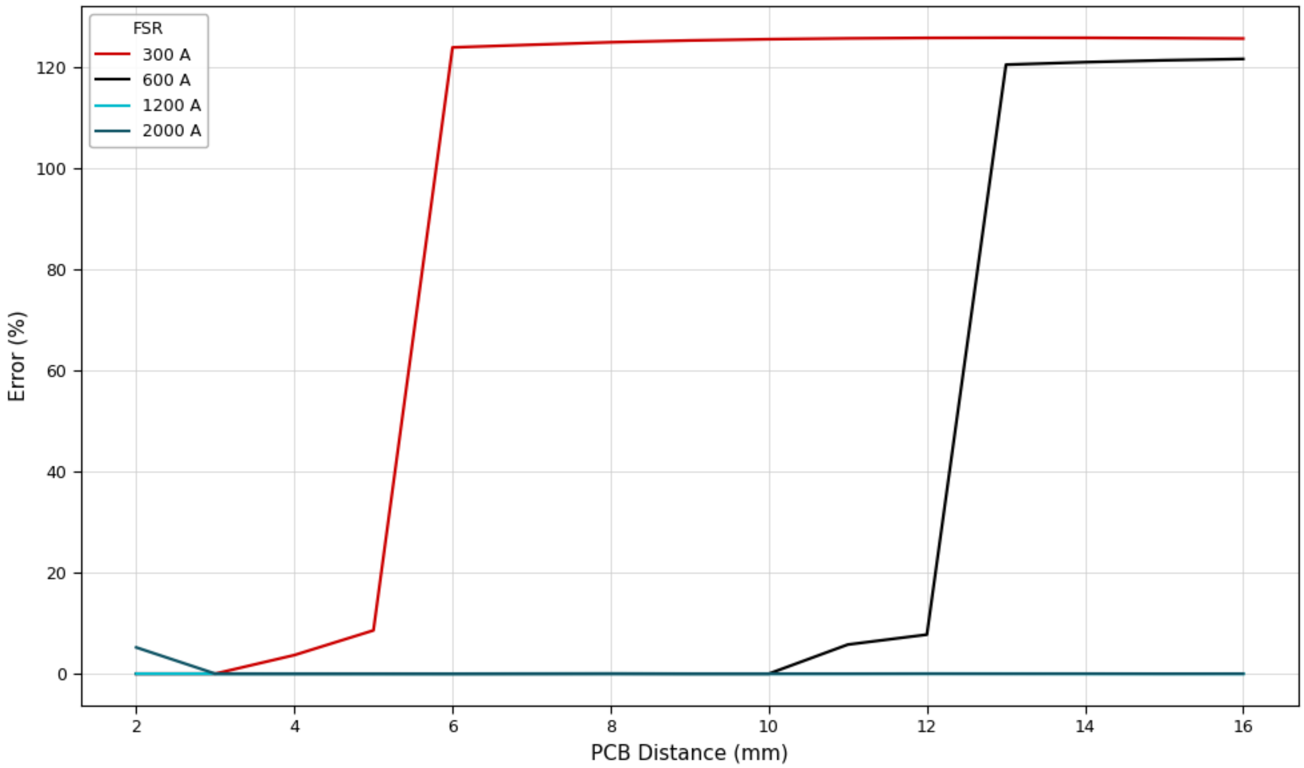

Figure 6-5. Error vs Distance to PCB (different FSRs)

Figure 6-6 shows the error vs different device spacings when the distance from the bus bar to the sensor PCB is fixed at 4 mm. Device spacing is not a limiting factor at 600 A, 1200 A, and 2000 A FSR. At 300 A FSR, however, placement beyond 11 mm from the bus bar center produces significant errors. This occurs because lower FSR ranges require higher gain to reach full scale (VS), making the device more sensitive to signal attenuation over distance.

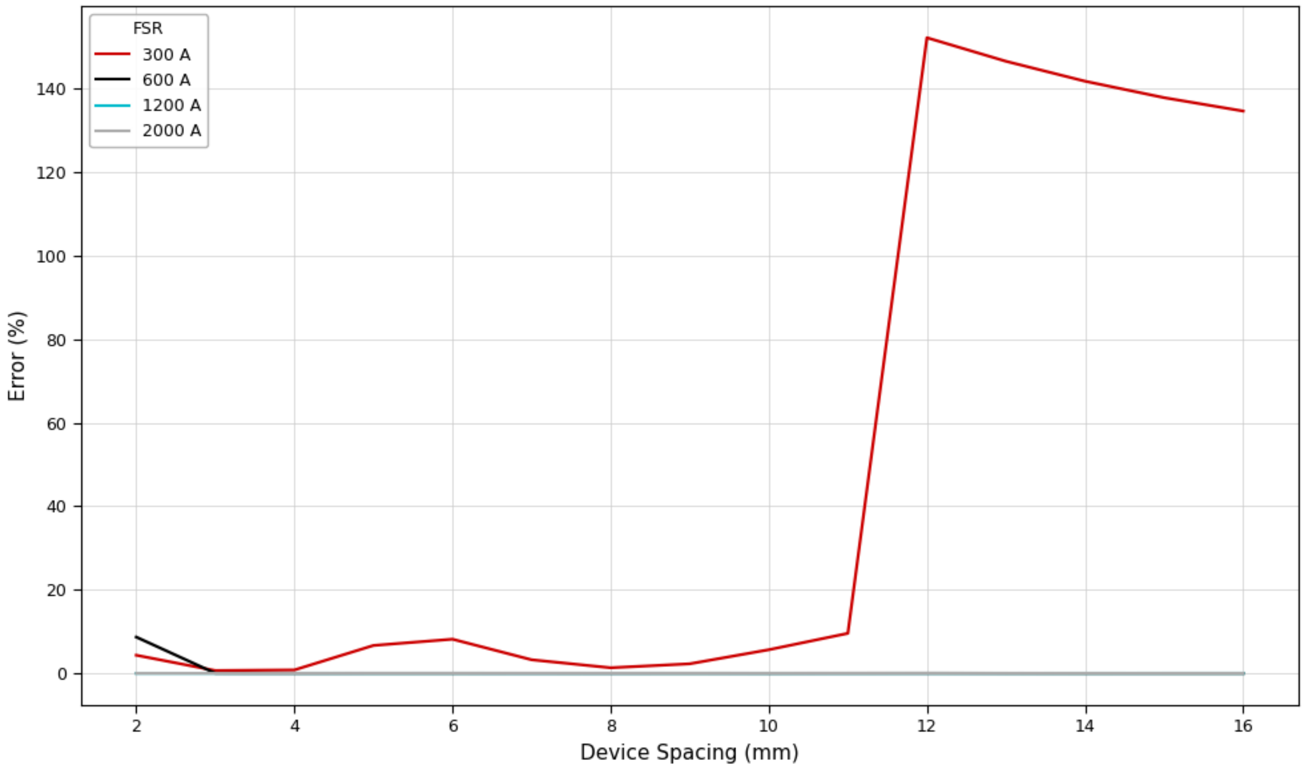

Figure 6-6. Error vs Device Spacing (different FSRs)

6.1.3.3 Plot Similarities

The four plots in Section 6.1.3 show that the error vs PCB distance plots when varying the device gain or varying the FSR look the same as do the two error vs device spacing plots. In Figure 6-3 the FSR was fixed and looks almost identical to Figure 6-5 where the device gain variant was fixed. It is known that the gain of the A1 device variant is half of the gain of the A2 device variant. The shift from the lines between A2 and A1 in Figure 6-3 are identical to that of the shift of the lines from an FSR of 600 A to 300 A in Figure 6-5. When the FSR is halved, twice the gain is needed to get the same results. Therefore a halving of the FSR shows the same characteristics in the plot as a halving of the gain (choosing a lower device gain variant).

6.1.4 Gain Considerations

When simulating it is important to find a location where the Gain 2 values for each device remain less than 16128. This provides headroom for two critical functions: frequency compensation circuitry to correct amplitude errors that grow with frequency, and tolerance margin to account for differences between the simplified 2D DC simulation model and real 3D bus bar geometry, PCB stack-up variations, and assembly tolerance. Systems with Gain 2 values exceeding 16128 leave no buffer for these corrections, which can result in frequency-dependent errors that cannot be corrected by the TMCS2100-Q1's frequency compensation scheme. If sensor placement results in high Gain 2 values, consider moving the sensors closer to the bus bar to increase gain margin, or select a higher-gain device variant (A2 or A3) to reduce the overall gain requirement.

7 Simulation Tools

The design guidelines outlined in this document represent best practices for minimizing errors, but they cannot predict the unique electromagnetic environment of a specific system. Bus bar material properties, PCB stack-up details, proximity of other conductors, and thermal management structures all influence the final system performance. Therefore simulations are recommended.

Both of the simulation tools described here are located on the TMCS2100CHAREVM product page.

7.1 DC Simulation Tool

TI has created a DC simulation tool to help users assess the feasibility of system designs and IC placement.

To use the DC simulation tool the full-scale range current and supply voltage should be set based on the system requirements. If there is design flexibility a spacing for the sensors should be chosen and the horizontal and vertical displacement values should be set to 0 mm. The sweep min and sweep max can then be set (recommend at 3 mm and 11mm) and the error vs PCB distance can be plotted. This will provide an idea of how close/far the sensor PCB can be placed for the chosen full-scale range and device gain variant chosen.

After this the sensor PCB distance can be chosen and fixed in the tool and the error vs device spacing can be run to find a spot with minimum errors from displacement, noise, and device variation.

Detailed instructions for this tool are located in the user's guide that is attached in the tool download.

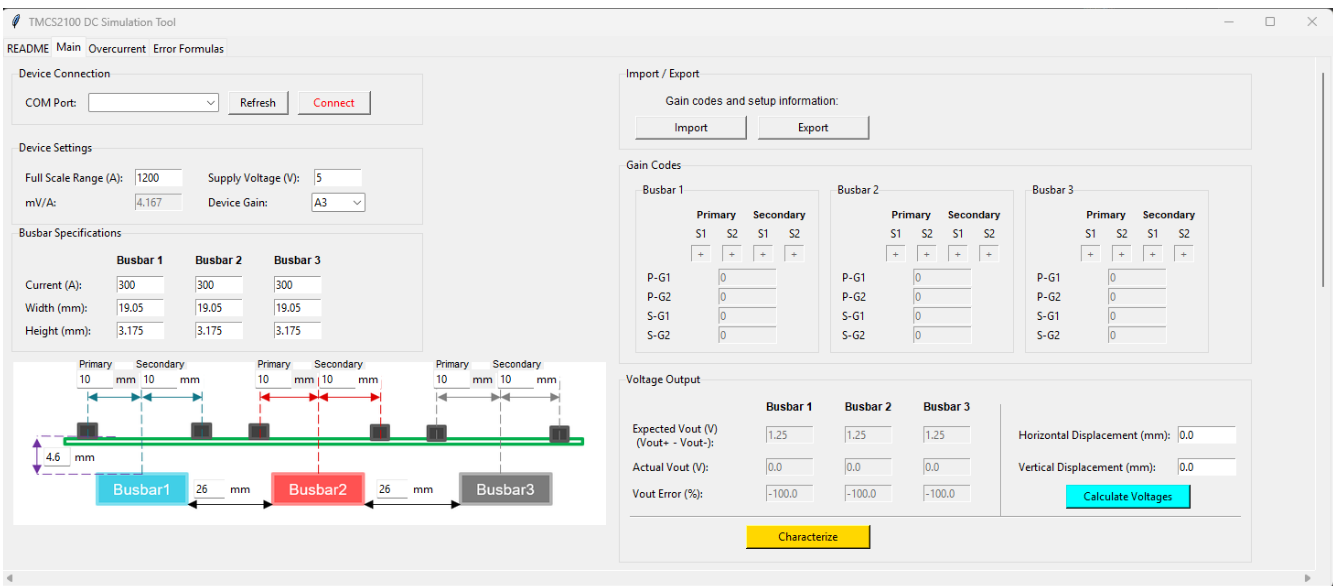

Figure 7-1. DC Simulation Tool

7.2 AC Simulation Tool

For complex designs it is recommended that 3D AC simulations be run to get a better understanding of how eddy currents and surrounding conductors will impact the specific system design. TI has created an AC simulation tool to help with this evaluation. The user should upload their model into an ANSYS Maxwell3D project. The tool will help the user properly configure their project file and collect data to predict real world characterization results.

Detailed instructions for this tool are located in the user's guide that is attached in the tool download.

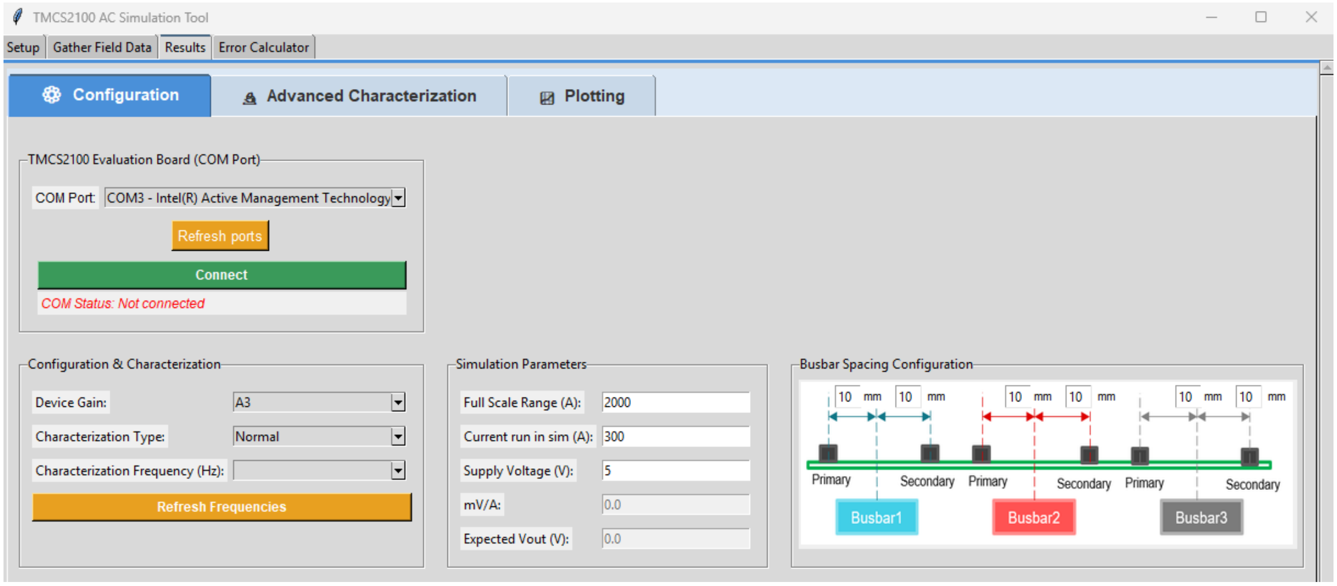

Figure 7-2. AC Simulation Tool

8 Characterization Requirements

The TMCS2100-Q1 requires a system level characterization. For a DC system, the user needs to be able to run DC current down each phase of the system. For an AC system there are two options for characterization: standard and profile. For both characterization methods a high precision reference current source is needed.

Additionally, the user will need connections to the analog outputs of each device and the I2C lines for communication during characterization.

The standard method of characterization requires a user to be able to run AC current down one phase of their system at a time. Using the TMCS2100CHAREVM-GUI the user will follow prompts to characterize the system. The user should collect data at different frequencies to give the system information to characterize over the frequency range.

In profile mode characterization the user can run current down all three phases at once in the forward direction, emulating the current seen during operation, and then repeat the process with current running in the reverse direction. Data for this can also be collected over multiple frequencies.

The characterization processes are described in detail in the TMCS2100CHAREVM User's Guide.

9 References

1. TMCS2100-Q1 Datasheet
2. TMCS2100CHAREVM User's Guide