TRANSIENT CURRENT BEHAVIOR IN APPLICATIONS USING THE ALLEGRO CORELESS ACS37610 DIFFERENTIAL CURRENT SENSOR

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INTRODUCTION

Allegro's coreless current sensors are automotive-qualified, accurate, and easy-to-integrate contactless solutions for measuring currents up to thousands of amperes—without the need for a magnetic core or shield. To reject stray magnetic fields, this family of sensors measures the field difference between two Hall elements within the sensor. With offerings like the ACS37610 and its 250 kHz bandwidth, the Allegro family of coreless current sensors is ideal for motor control, electrical, or hybrid vehicle applications.

Although Allegro coreless sensors can be used with any busbar, this application note explains how the conductor design can impact the response time of the current measurement for coreless current sensing applications and provides examples of response time to transient current for two types of conductors—a busbar and a multilayer copper trace on a PCB.

This analysis applies to the family of Allegro coreless current sensors. For simplicity, the high-accuracy, low-noise ACS37610 [1] coreless current sensor is used as an example. For specifications related to other Allegro coreless current sensors, refer to the product datasheet at allegromicro.com.

BACKGROUND

Conductor design can impact the response time of the current measurement of the Allegro coreless sensors. To achieve the best performance (accuracy, high signal-to-noise ratio, high bandwidth, fast response time, low sensitivity to mechanical tolerances, etc.), the busbar design must include certain features. Some recommendations are provided in the application note "Busbar Geometry and Design Techniques for Coreless Differential Current Sensors". [2]

For the busbar discussed in this paper, the sensor is placed over a notch in the current-carrying conductor (copper is used here), as shown in Figure 1. The notch (i.e., a local reduction of the cross section) is intended to locally increase the current density and the magnetic signal measured by the IC. Busbar notch dimensions are defined in Figure 2 and Figure 3, and the magnetic field induced by current, I, flowing in the busbar is sensed as shown in Figure 4.

The example sensor used here—the ACS37610—has two Hall plates sensitive along the Z axis, situated 2.58 mm away from each other. The left Hall plate measures magnetic field B_L and the right Hall plate measures magnetic field B_R. The output of the sensor, V_{OUT}, is proportional to the differential magnetic field, ΔB:

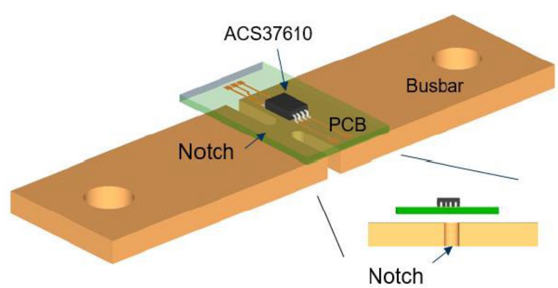

Figure 1: System overview

[1] https://www.allegromicro.com/en/products/sense/current-sensor-ics/sip-package-zero-to-thousand-amp-sensor-ics/acs37610
[2] https://www.allegromicro.com/-/media/files/application-notes/an296194-acs37610-busbar.pdf?sc_lang=en

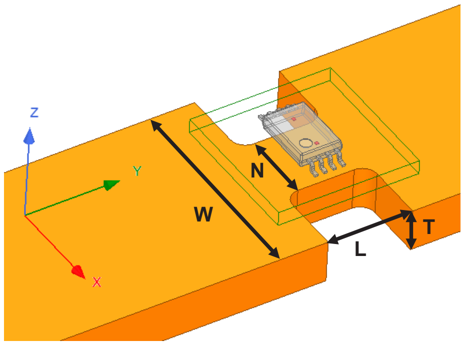

Figure 2: Description of busbar and notch parameters

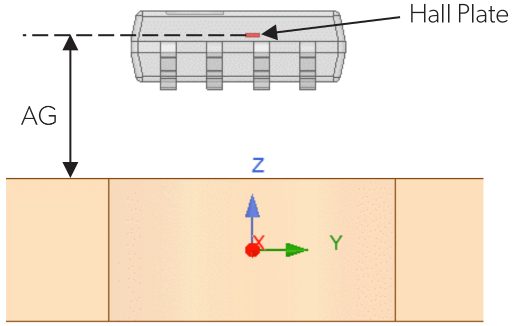

Figure 3: Air gap definition

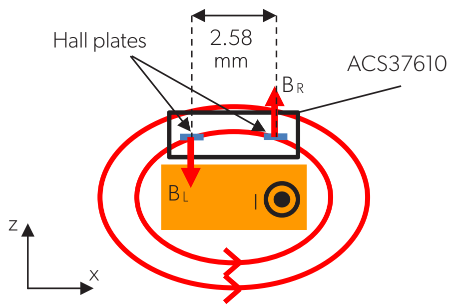

Figure 4: ACS37610 measurement principle

Equation 1:

$$\Delta B = B_R - B_L; \text{ and}$$

Equation 2:

$$V_{OUT} = \alpha \times \Delta B,$$

where α is the sensor's output sensitivity to the magnetic field.

The relationship between the applied current and the differential field is given by the coupling factor, CF:

Equation 3:

$$\Delta B = CF \times I.$$

In this application note, the output of the ACS37610 device is observed and simulated while a transient current flows into the conductor. Although response time depends on the internal bandwidth of the device, it is also impacted by the bandwidth of the conductor. Indeed, with fast-varying input currents come eddy currents that tend to increase the overall response time of the system.

The current density distribution shown in Figure 5 is for a busbar design with notch width N = 3 mm, notch length L = 6 mm, and conductor thickness T = 4 mm at t = 1 µs, for a current rise time of t_R = 1 µs with I_{MAX} = 1000 A. (For the definition of t_R, see Figure 6.) As expected, the current distribution is greater on the sides of the notch due to eddy current induced by the quickly varying input current.

Important definitions are discussed next, and currents and their effect on response time are discussed later in this application note.

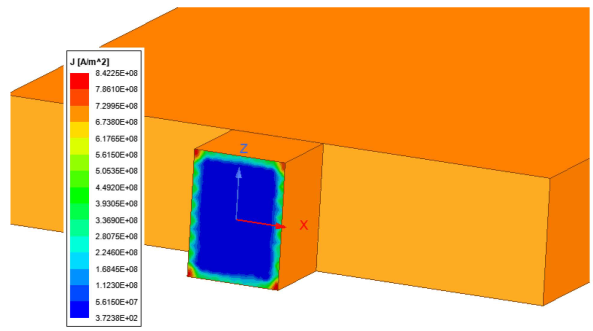

Figure 5: Current distribution in the notch at t = 1 µs with t_R = 1 µs and I_{MAX} = 1000 A

DEFINITIONS

Understanding the effect of input and eddy currents on response time requires first defining relevant types of response times:

- ***90% response time (t_{90} response time).*** This is the time difference between the normalized output and the normalized input current at 90% of the maximum value (steady state). The definition of t_{90} is illustrated in Figure 6 for a normalized input current injected in the busbar and the normalized output. As shown, the input current starts at 0 A and ramps up to I_{MAX} in t_R seconds. The resulting response time is the sum of two contributions:
  - ***Sensor intrinsic response time to an input differential magnetic field.*** This response time is primarily governed by the IC internal clock, the amount of processing realized, and the IC bandwidth. The ACS37610 response time is typically 1.3 µs.
  - ***Conductor response time to a varying input current.*** This response time is primarily governed by Lenz's Law—Any varying current induces eddy currents in the conductor, and these eddy currents introduce a delay on the total current flowing into the conductor.

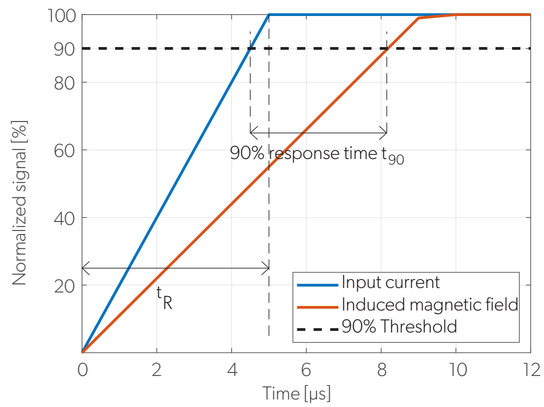

Figure 6: Input current rise time (t_R) and definition of 90% response time (t_{90})

REFERENCE DESIGNS

PCB Reference Design

The Allegro PCB reference notch design in this application note (see Figure 7, Figure 8, and Figure 9) is optimized for the best DC, AC, and transient current performance operating at 100 to 200 A. The dimensions are N = 3.5 mm and L = 2.5 mm. The current flows into seven inner layers of 35 μm copper, while the top layer (not shown in Figure 8) is used for device connections.

The t_{90} response time demonstrated through electromagnetic simulations is reported in Figure 10; it is expected to be ~1.4. μs, and the coupling factor is expected to be CF = 900 mG/A. The corresponding measurement given in Figure 11 shows a t_{90} response time of ~1.9 μs. The measurement and simulation are in good agreement.

Where the simulations and measurements differ, two predominant factors are at play: 1) the simulations do not consider internal delay of the device (~1.3 μs); and 2) the input step current considered in the simulations assumes a constant current rise time, which means that 100% of its value is reached faster than the real current step-generated during the measurements and, thus, eddy currents are over-simulated compared to reality. (This is further discussed in "Response Time Sensitivity to Input Current".)

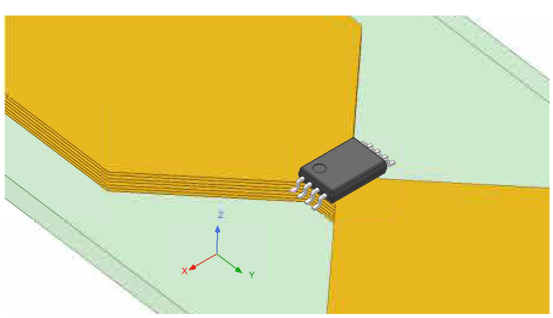

Figure 7: PCB reference design—Overall view

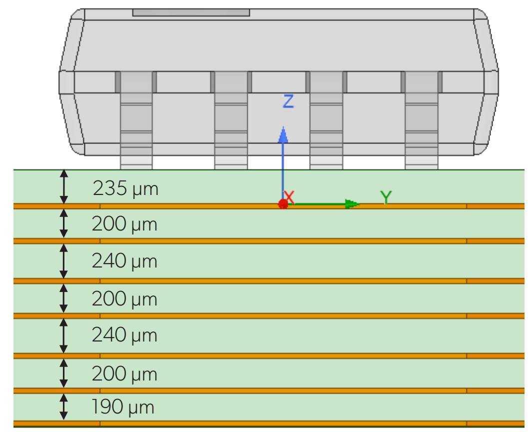

Figure 8: PCB reference design—Details of current-carrying layers

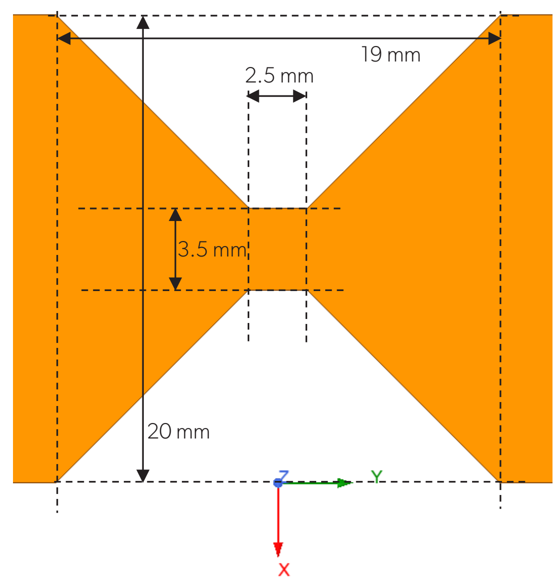

Figure 9: PCB reference design—Details of notch

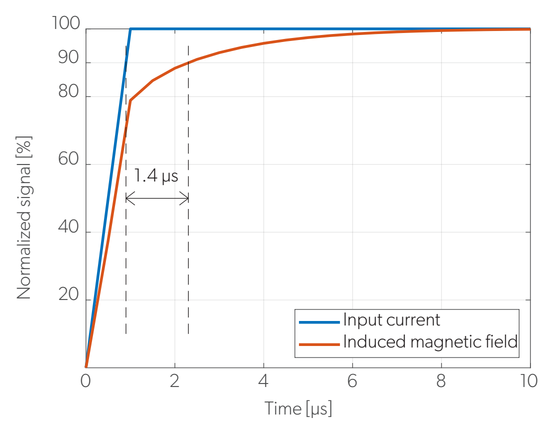

Figure 10: PCB reference design—Simulation of t_{90} response time to a t_R = 1 μs rise current; effect of eddy current only (sensor response time not included)

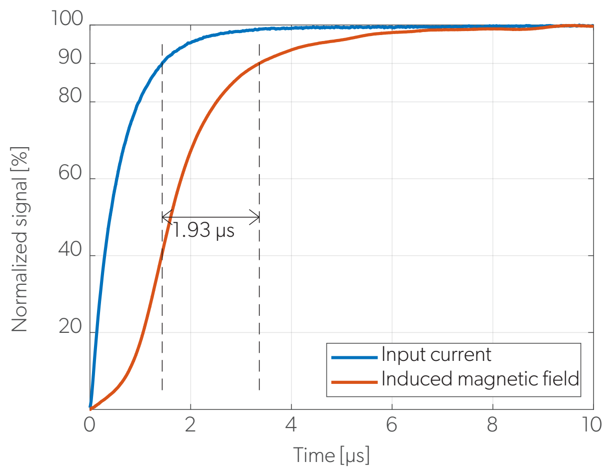

Figure 11: PCB reference design—Measured results of t_{90} response time to a t_R = 1 µs rise current

Busbar Reference Design

The Allegro busbar reference notch design is optimized for best DC, AC, and transient current performance. It is also designed for optimal thermal and mechanical behavior. The notch dimensions are N = 3 mm, L = 6 mm, and T = 4 mm (see Figure 2). This reference busbar with notch is recommended for high-primary-current and high-frequency applications, such as inverters.

Using electromagnetic simulations of the reference busbar, the t_{90} response time is reported in Figure 12 for an air gap (AG) of 2 mm;

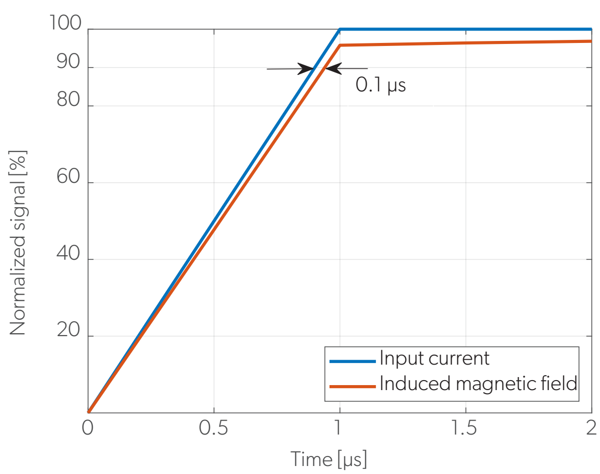

Figure 12: Busbar reference design—Simulation of t_{90} response time to a t_R = 1 µs rise current at AG = 2 mm; effect of eddy current only (sensor response time not included)

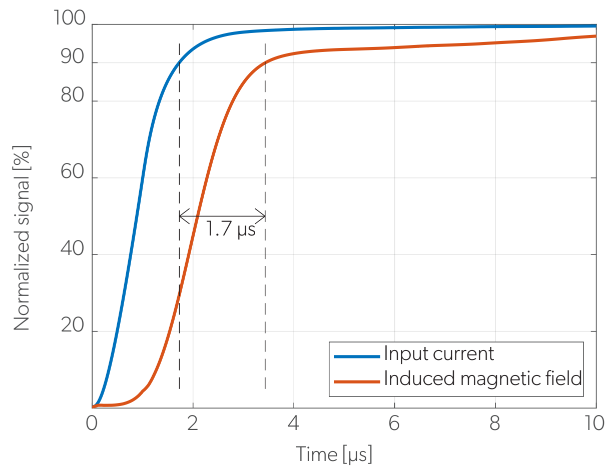

Figure 13: Busbar reference design N = 4 mm—Measured results of t_{90} response time to a t_R = 1 µs rise current

The t_{90} response time is expected to be ~0.1 µs, and the coupling factor at this air gap is expected to be CF = 300 mG/A. The corresponding measurement in Figure 13 shows a t_{90} response time of ~1.7 µs. Because the simulated response time does not include the ~1.3 µs response time of the example ACS37610 sensor and because the simulated and real input currents are different, the measurement and simulation may not appear to be in good agreement. However, the order of magnitude of the measurements—including the IC response time—and the simulation are similar: ~1.5 µs.

DISCUSSION

Response Time Sensitivity to Conductor Design

Electromagnetic simulations are presented here to illustrate the influence notch width N, notch length L, and conductor thickness T have on the observed response time. Busbar width W is fixed at 18 mm. The sensor response time is not considered in these electromagnetic simulations.

The t_{90} response times for various dimensions of the notch are shown in Figure 14 for an input current with a 1 µs rise time. The main contributor to the t_{90} response time is clearly notch width N. The response time also tends to increase as thickness T increases and to decrease as notch length L increases. Generally, the response time is faster when eddy currents are reduced, which occurs when there is little space to expand in the directions perpendicular to the input current flow. This is illustrated in the zoom of the case of T = 3 mm, AG = 2 mm, N ≤ 4 mm shown in Figure 15.

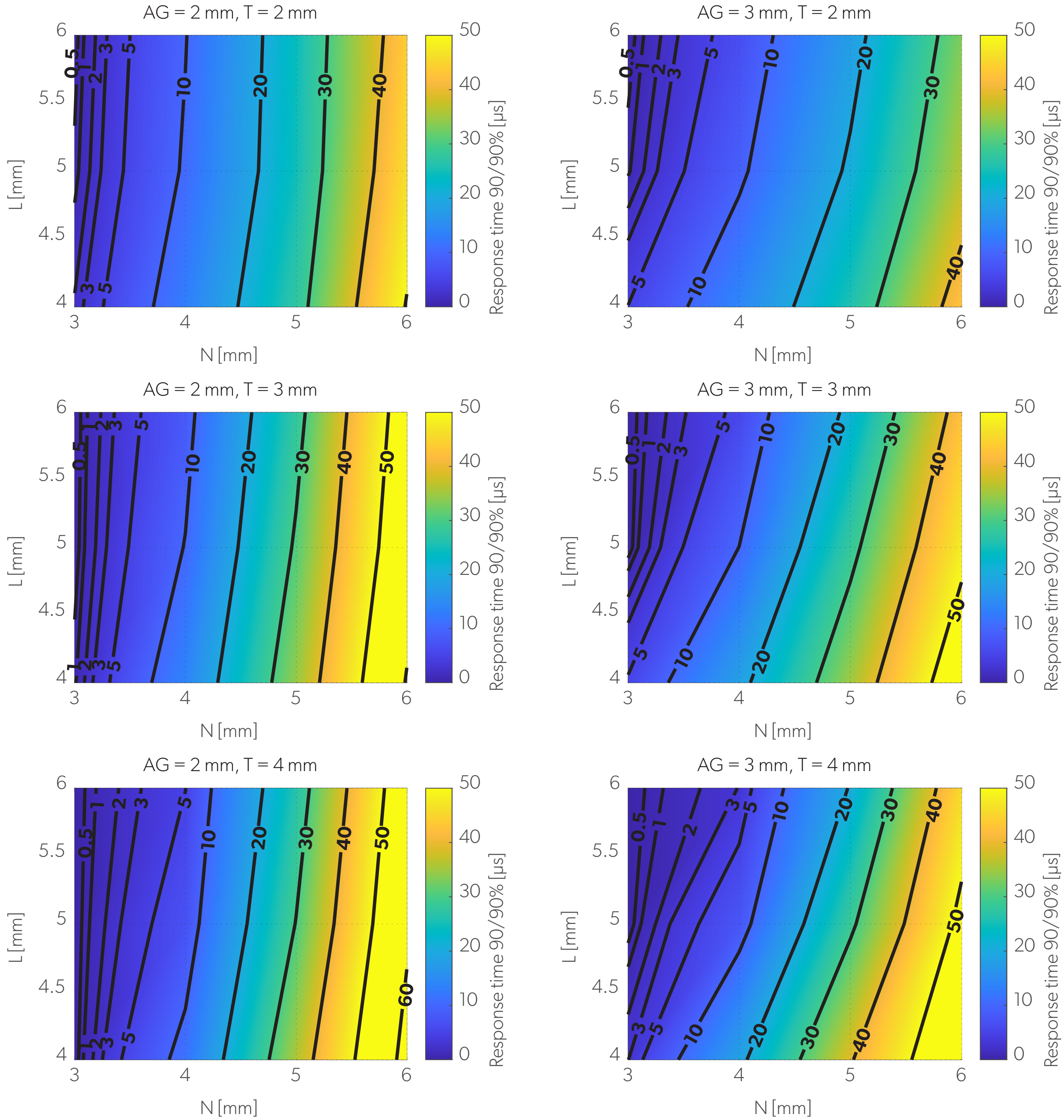

Figure 14: Notch t_{90} response time to a 1 µs rise time current versus N, L, T, and AG; effect of eddy current only (i.e., sensor response time not included).

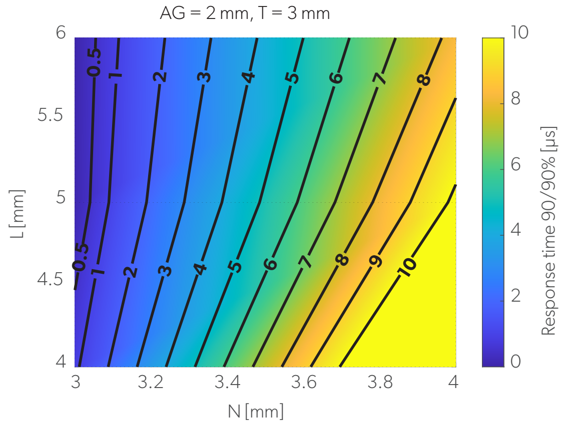

Figure 15: The t_{90} response time to a 1 μs rise time current versus N and L, with T = 3 mm and AG = 2 mm; effect of eddy current only (sensor response time not included)

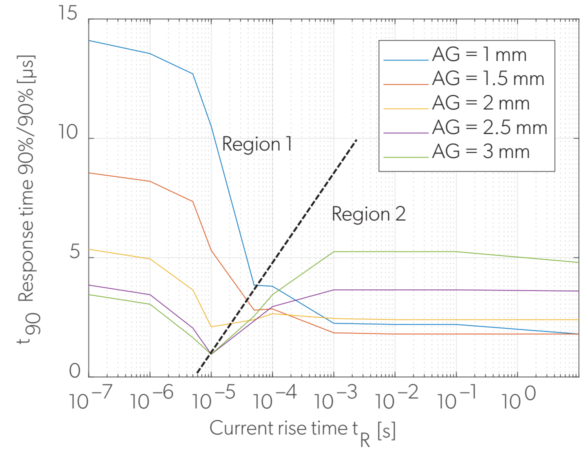

Figure 16: t_{90} response time for N = 4 mm, T = 4 mm, L = 6 mm notch versus current rise time t_R (sensor response time not included)

The response also tends to be faster with larger air gap because the local eddy currents are less visible from farther away. For notch width N = 3 mm and notch length L ≥ 5 mm, an extremely fast t_{90} response time can be achieved (< 0.5 μs) whatever the air gap and notch thickness.

Response Time Sensitivity to Input Current

The influence of magnitude and rise time on response time is illustrated in this section using electromagnetic simulations only (i.e., sensor response time is not included).

For a busbar with N = 4 mm, L = 6 mm, T = 4 mm, the typical t_{90} response time is 5 μs. (For the purpose of making the effect more visible, this design is deliberately wider than the reference design.) The t_{90} response time is shown in Figure 16 for various current rise times for several air gaps, with 1000 A input current in all cases. The two regions in this plot correspond to two modes of operation for the induced magnetic field.

The first mode of operation ("Region 1") has a fast current rise time—less than ~50 μs (depending on air gap). This mode corresponds to Figure 17, where the input current reaches its plateau before the induced magnetic field reaches 90% of its maximum value; at that point, the magnetic field is no longer pulled by the increasing input current and therefore increases slowly, leading to a visible "settling time" between 90% to 100% of the signal. This effect does not depend on maximum current I_{MAX} of the ramp but only on its rise time, as shown in Figure 18.

The second mode of operation ("Region 2") in this example starts after ~50 μs and corresponds to the case where the output signal reaches 90% before the input current reaches its plateau (as in Figure 19). The current rise time is so slow that the generation of eddy currents is minimal, and the magnetic field follows the current very well. Nevertheless, these eddy currents

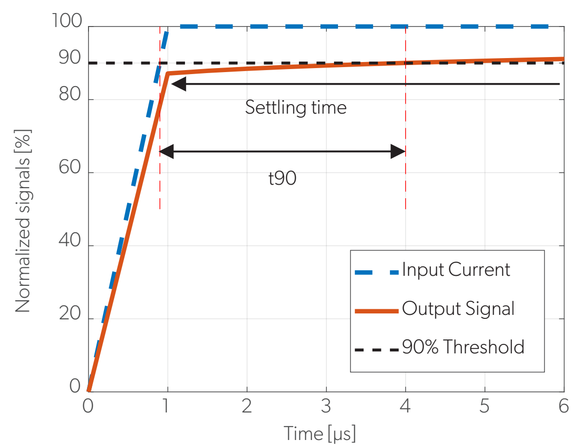

Figure 17: Input current with t_R = 1 μs and 90% response time (t_{90}) definition

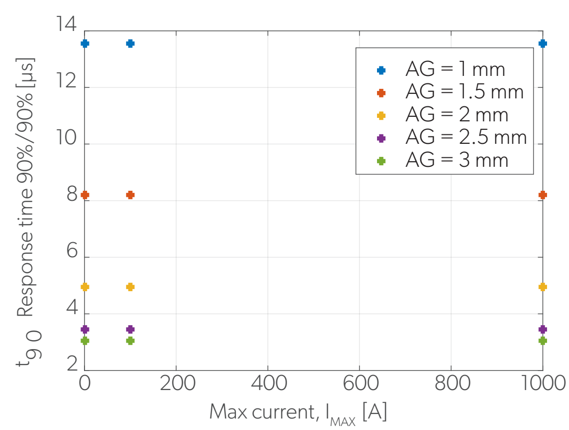

Figure 18: t_{90} response time versus maximum ramp current I_{MAX} for t_R = 1 μs, N = 4 mm, T = 4 mm, L = 6 mm

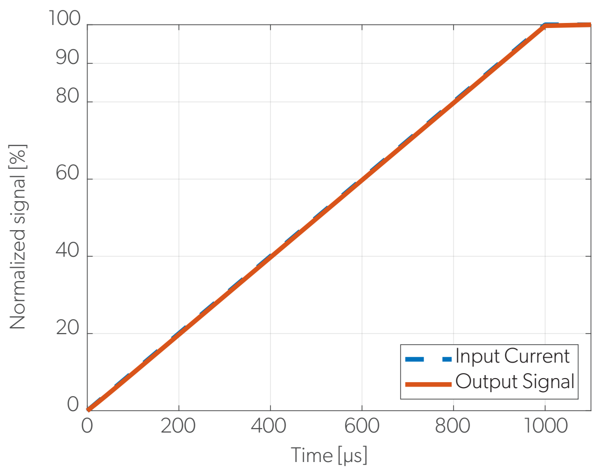

Figure 19: Output signal for t_R = 1 ms, N = 4 mm, T = 4 mm, L = 6 mm, AG = 2 mm, and I_{MAX} = 1000 A

still induce a delay, which is constant whatever the current rise time, but depends on the air gap.

The "settling time" of the induced differential field corresponds to the time it takes for the field to reach a steady state or 100% of its final value (i.e., the differential field at the constant current value) from the time the current stops increasing (t_R).

Consideration for Overcurrent Detection and Response Time

While the effect of rise time on the 90% response time described here should be considered, it does not necessarily limit the system response time to overcurrent events in application for the following reasons:

- In real-life applications, current rise time is limited by circuitry switching time and overall cable impedance. As demonstrated in the measurements, the current rise is generally not as simple as a first-order slope, which limits the eddy current and the theorical "settling time" effect.
- When considering an overcurrent event, the current generally exceeds the maximum current considered in the full-scale definition; thus, the 90% level with respect to this full-scale (device output) will be reached before the input fault current reaches its maximum, resulting in the mode of operation shown in Region 2 in Figure 16. In other words, the overcurrent flag would be triggered before the induced magnetic field enters the settling-time region. Thus, the 90% response time definition may not always apply to the estimate of the response time to an overcurrent event.

The 90% response time behavior could be approached similarly to the fusing time of an electrical fuse, which is faster when the current exceeds the fuse range (i.e., the overcurrent condition) than when the current reaches and stabilizes to 100% of the fuse range (i.e., the overload condition).

A good methodology for response time estimation should consider an overcurrent value greater than the full-scale range definition. Additionally, for cases where current settling time has limited effect, the considered response time threshold could be changed from 90% to 80%.

CONCLUSION

In many current sensing applications, system response time is important to protect a circuit against overcurrent events and to follow quick changes in the current that is to be sensed.

This application note has shown how eddy currents within the conductor affect response time and has explained how eddy currents should be considered in the design phase of the current-carrying conductor (busbar or PCB copper traces) for coreless current sensing applications. The concept of sensed current "settling time" related to eddy current has been discussed, highlighting the effect of fast current rise conditions. Finally, to achieve response time estimations closer to real-life application, including conditions like overcurrent events, the limitations of the response time definition at 90% of the full scale have been explained.

From a general standpoint, to generate fast response times, the eddy currents induced inside the conductor must be limited. However, as eddy current distribution over frequency and the corresponding induced magnetic field are difficult to guess in a real system, it is impossible to give a full set of predictions for the variety of possible conductors. Nevertheless, the general guidelines are to employ a conductor with features that are as thin, narrow, and long as possible (within the limits of the thermal envelope).

For a notch design, the recommendations are to use N = 3 mm and L = 6 mm to achieve the best response time. In this case, the busbar thickness is mostly irrelevant.

For further questions or support, contact an Allegro representative. [3]

[3] https://allegromicro.com/contact-us

Revision History

Number	Date	Description
–	April 20, 2022	Initial release
1	May 31, 2022	Minor editorial update to Figure 6 (page 3)