

Calc-U-Bar

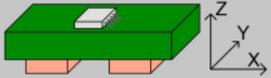
Magnetic Field Calculation Tool for CFS1000 Current Sensor Busbars

CFS1000 Calculations - Tool
Version 1.8 / 2018



base settings

dimensions in millimeter



CFS1000

thickness: 2

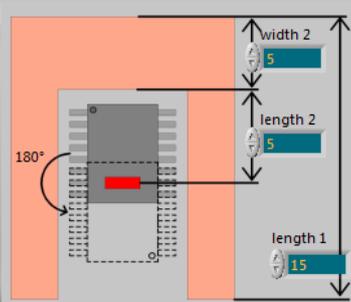
width 1: 4

gap: 2

distance: 1

CURRENT [A]: 100

tolerance views



advanced settings

example settings

NO

differential field (x-field): 1892

impact on stabilizing field (y-field): -336,1

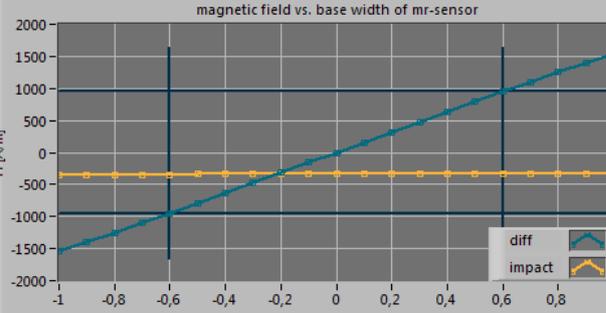
current density [A/mm²]: 12,5

target values:
differential field: 1920A/m +/-190A/m
impact on stabilizing field: 0A/m +/-500A/m

offset differential field

symmetry of impact field

magnetic field vs. base width of mr-sensor



H [A/m]

base width [mm]

diff

impact

axis scaling

base width maximum: 1

base width minimum: -1

H [A/m] maximum: 2000

H [A/m] minimum: -2000

Info

Simulate



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1. Introduction

Calc-U-Bar is a customer support tool, which allows first analytical design approaches to magnetic requirements of a customized current measurement solution with Sensitec CFS1000 current sensors. The tool operates using the National Instruments LabVIEW® runtime environment.

Based on magnetic field calculations using Biot-Savart's Law, it can be used for first dimension estimations of the U-shaped busbar for operating the CFS1000. Additionally, the influence of different current feeds can be investigated without the need for excessive 3D FEM-simulations (three-axis angle variation for the current feed is possible).

It also includes the possibility to estimate magnetic crosstalk or interference from adjacent current paths or field sources, which gives the possibility, to define specific spacing requirements for multiphase arrangements. At the same time, the influence of a varying sensor position relative to the busbar is calculated. This gives an idea towards process related positioning tolerances and their influence on the magnetic fields components.

This user guide should be used in combination with the CFS1000 data sheet and application note. For more information please visit us at www.sensitec.com.



Calc-U-Bar user interface

Installation Instruction

Download the simulation software “Calc-U-Bar” from our website www.sensitec.com. The download contains a compressed install package which can be extracted to any user specified folder destination. Run the setup.exe inside the folder “Calc-U-Bar_install” and follow the install instructions. After the installation procedure, the program can be started via the Windows Start Menu.

Limitations

Calc-U-Bar is a customer support tool aiming at simple feasibility studies. It does not consider aspects like:

- Isolation topics
- Magnetic or electric shielding
- Usage of ferrous materials close to the sensor
- AC-effects or inhomogeneous current density distributions (field asymmetries)
- Thermal issues due to power losses and local hot spots

Before integrating the CFS1000 sensor into a final applications/series products, it is recommended to contact the Sensitec sales department and to request an advanced engineering support.

Features

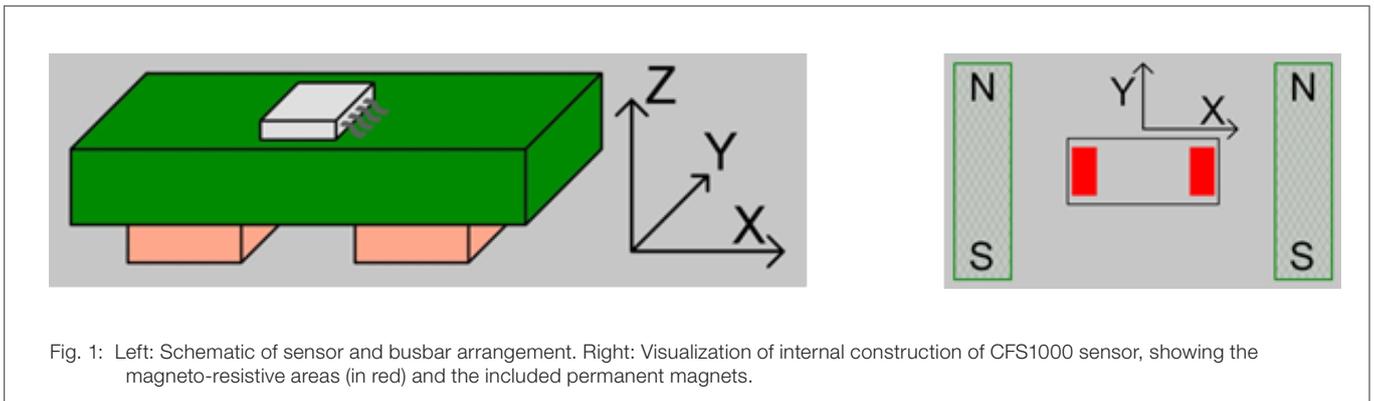
- Simple simulation and estimation of required busbar design
- Optimization of busbar geometry
- Takes into account positioning tolerances
- Easy to use graphical user interface
- For first considerations, no 3D FEM-simulations needed
- Simple installation

Applicable Documents

- CFS1000 Datasheet
- CFS1000 Application Note

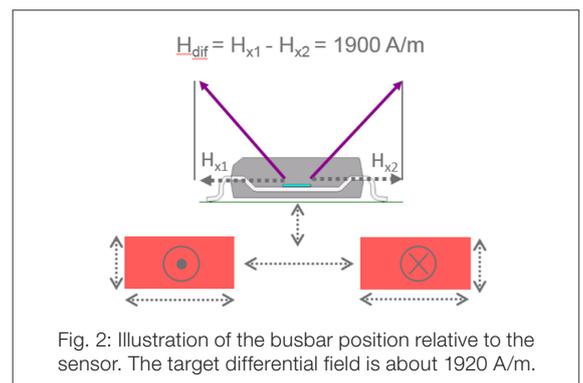
2. Basic Knowledge – CFS1000 and MR-Principle

- The working principle of the CFS1000 current sensor is based on a compensated **differential field (x-field)** measurement. The primary current to be measured is fed below the sensor through a U-shaped current conductor, as for example a busbar. In this way, a magnetic differential field (gradient) is generated between both sides of the conductor, which is measured by the sensor element. By measuring the field gradient at two measurement points being in close proximity, an excellent stray field immunity is achieved. The modulation of the sensor element is compensated by a magnetic counter field on the AMR-sensor chip. The value for this required compensating current is the proportional measure for the primary current and represents the output signal of the sensor. Based on the compensation of the primary field (closed-loop principle), a high linearity and low temperature dependency is realized. The CFS1000 is a small, light sensor robust against homogeneous stray fields and temperature variations and at the same time has remarkable low power losses.
- A single MR-resistor changes resistance as a function of the strength of the magnetic field vector in x-direction. The Wheatstone-bridge arrangement inside the CFS1000 has two active MR-areas on the chip (red markings, see Fig. 1), which are sensitive to the difference of the magnetic field in x-direction. The average distance of the MR areas is 1.24 mm (base width). The CFS1000 works best, when the nominal field is targeted to a gradient of 1.6 kA/m/mm (2 mT/mm), leading to target value of 1920 A/m \pm 190 A/m (approx. 2.5 mT; see Fig. 2) field difference over 1.2 mm. The origin of the coordinate system is located in the center of the MR-sensor surface (in xy-plane). The busbar is always located in a parallel plane below the sensor position (shift in z-direction).

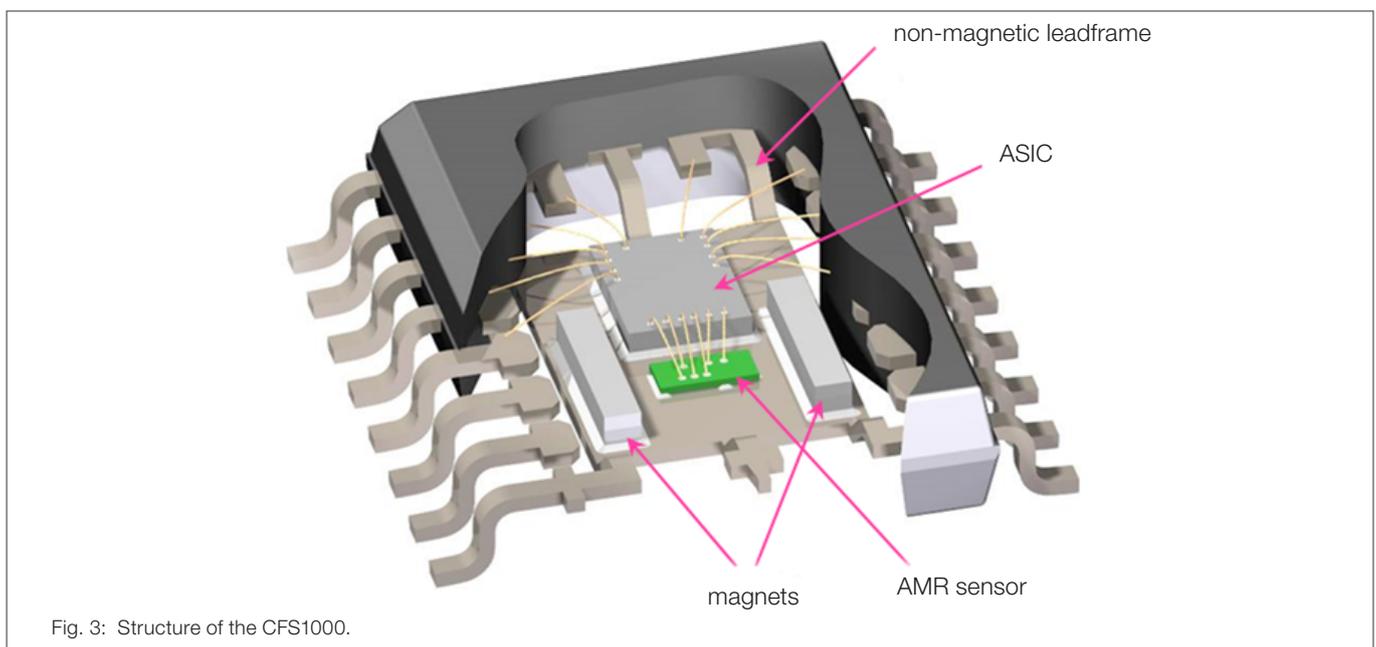


- MR resistances have a privileged magnetization direction which can flip about 180°, if an external magnetic field is present, pointing in the opposite y-direction of the **stabilization field (y-field)** and being larger than this. In closed loop operation, this would lead to a positive feedback situation, where the output of the CFS1000 would flip to the opposite voltage saturation rail. This operation error is a temporary effect, lasting as long as such field conditions are present. Permanent damage would require fields above 3 T. To avoid the flipping error, the MR resistances are biased by a stabilization field generated from two permanent magnets inside the package. At sensor position, their field is typically 3 kA/m in y-direction. As mentioned before, the sensor can still flip as soon as an external field in y-direction becomes larger than the stabilization field. As the sensor can measure above 3 times the nominal field gradient and is supposed to operate stable for over currents up to 5 times the nominal current, Calc-U-Bar sets \pm 500 A/m as a maximum allowed impact on the stabilization field.
Note: For applications where the maximum current is clearly limited to less than 5 times the nominal current, or stable measurement in over current situations is not required, this limit may be expanded. This will allow the construction of smaller busbars.

- Symmetry of the magnetic field relative to the chip center is not mandatory, due to differential field principle, but nevertheless, will reduce non-linearity for high current arrangements. For busbar systems targeted above 100 A nominal current, the magnetic field of the current feed may also reach field strengths above 1 kA/m at sensor position, which may cause inhomogeneous field strengths at a single MR-resistance, which have to be compensated using the compensation loop.



- 1 kA/m stray field at sensor position is a general experienced limit for keeping its impact below 1%, as this is the nominal field for one active chip area. The stray field immunity can be improved by applying a ferrous or Mu-metal shield. In this case, the Calc-U-Bar tool is no longer sufficient, why a 3D FEM-simulation is recommended.
- Ferrous materials in the environment of the CFS1000 may become a threat, due to their magnetic hysteresis, which may lead to a hysteresis in the characteristics of the current sensor.
- The skin effect may lead to field strength variations, generating a larger field gradient and thus affects the sensor. The result is an increasing gain over frequency (in frequency response or peaking) and overshooting in step response. Both can be compensated by the use of one or more RC-stages, attenuating higher frequency signals to the correct level. In general, AC-effects are not considered by Calc-U-Bar.
- For low nominal currents below 15 A and/or larger distances between the CFS1000 and the busbar, as may be required due to isolation layer constraints, it might not be possible to reach the target differential field using one U-shaped busbar. A smaller nominal gradient is possible as long as the signal to noise ratio is still acceptable or if noise can be filtered out for the relevant frequency range. However, a better solution is a busbar consisting of several windings or a coil in order to achieve the nominal field gradient. Calc-U-Bar can be used to do a raw design of such current paths. The first possibility is to simulate each winding as a single U and sum all the resulting gradient fields afterwards. The second possibility, more suitable for coil design, is to assume the coil being a massive U and to multiply the coil current by the number of windings. The field in y-direction in this case is less critical, as each winding has a feedback line compared to a U-shape, which produces a counter-field. Therefore, y-fields will cancel each other as long as the sensor lies somewhere in the center of the coil.
- Temperature has a certain effect on current measurements, even though drifts are factory calibrated. The remaining offset change of the CFS1000 is below $\pm 1\%$ over the complete temperature range. Thermal effects may influence the PCB thickness and therefore, will influence the differential field. Calc-U-Bar cannot forecast such events as it does not take into account thermal effects. Anyway, if a possible change in thickness is known or can be estimated, thermal effects can be simulated indirectly, using these expected values in the simulation.
- In general, the design of the current sensor arrangement has a big influence on power dissipation and thermal behavior. Calc-U-Bar will not cover such effects, nor give guidance on thermal or mechanical construction – as possible influences are too various for this calculation tool.
- The U-shape of the busbar is not mandatory. It is also possible to measure the differential field between two parallel feed lines if the current splits equally between them (conduction in the same direction) or if one feed is carrying the forward and the other the return current (assuming zero losses). In this case, a very large value (>1000 mm) must be assigned to parameter length2, in order to run the simulation without impacting the stabilization field.
- The CFS1000 is a closed-loop current transformer consisting of an AMR sensor chip, two bias magnets and a signal conditioning ASIC that are all packaged in a standard SMD SO16w package (Fig. 3).



3. Getting Started

The front panel consists of several input fields to define the busbar geometry and the nominal current. The same panel contains the output graphs of the simulated results.

Legend

1. Base settings (Fig. 4): Basic input window. Definition of busbar layout and nominal current.
2. Tolerance views (Fig. 5): Evaluation of differential field and impact on stabilizing field of possible sensor positioning errors in x-, y- and z-direction.
3. Advanced settings (Fig. 6): Additional options when considering a second sensor and/or different current feeds from x-, y- and z-direction.
4. Busbar geometry and current definition.
5. Simulation results for differential field (x-field), impact on stabilizing field (y-field), current density and result graph for magnetic field vs. base width of mr-sensor.
6. Software info.
7. Run simulation and simulation status.
8. Open predefined examples (may be used as a starting point for your own design).
9. Influence of sensor placement errors relative to the busbar (differential field and impact on stabilizing field; in x-, y- and z-direction).
10. 2nd sensor position and current feed option.

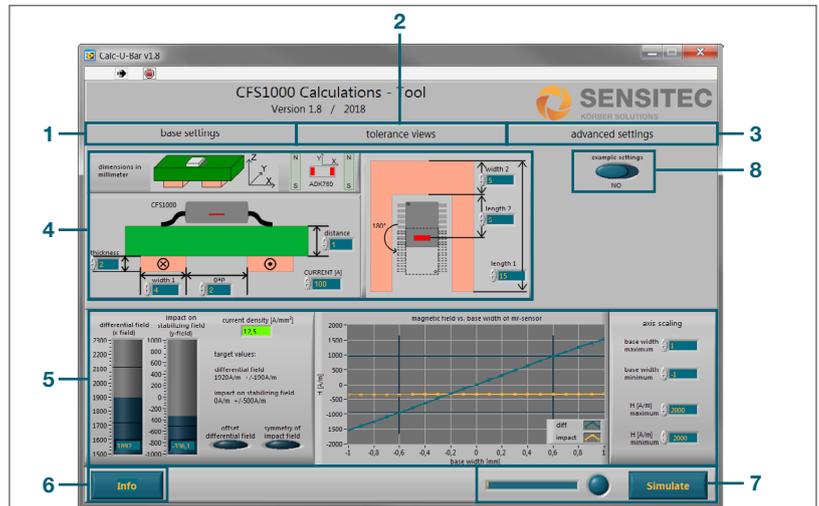


Fig. 4: Front panel after start up. Base settings.

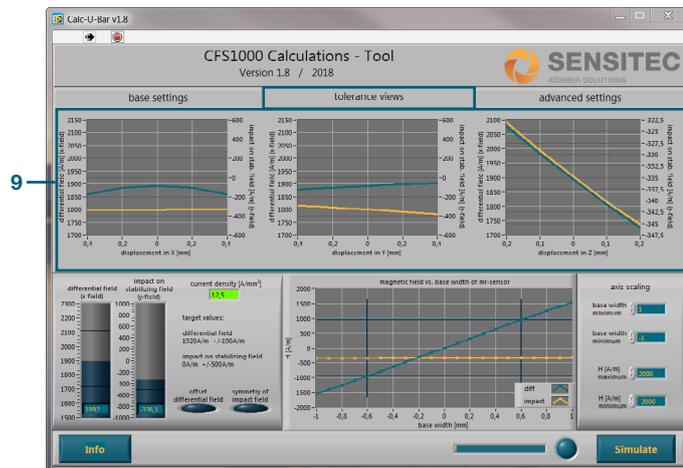


Fig. 5: Tolerance views.

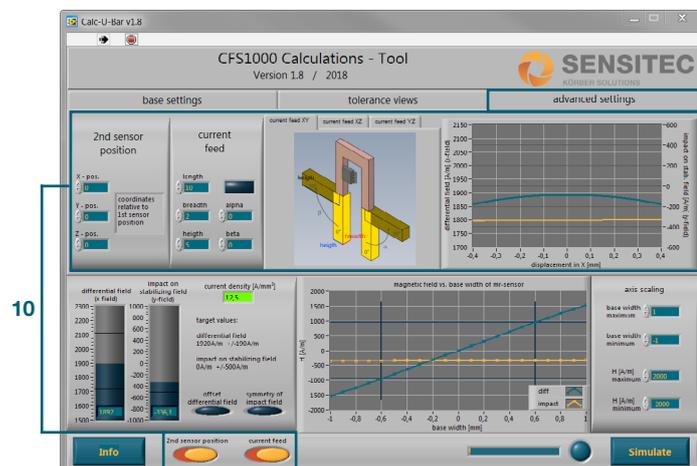


Fig. 6: Advanced settings.

4. Simulation Procedure

- Definition of **busbar geometry**. Note that the CFS1000 can be rotated by 180° without impact for the measurement and calculation (units in mm; see Fig. 7).
- Specification of **nominal current** (unit A).

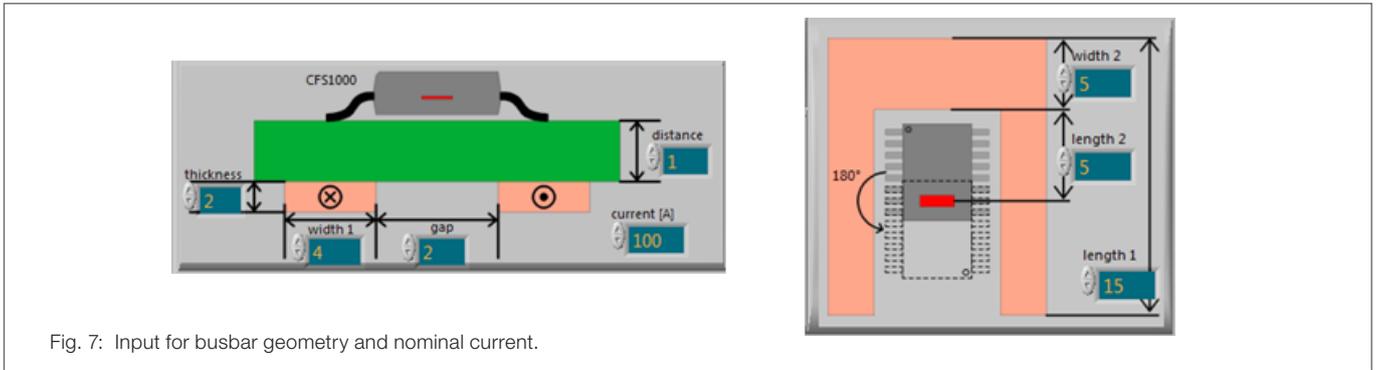


Fig. 7: Input for busbar geometry and nominal current.

- Start the simulation process by clicking **Simulate**. This process will take a few moments and is visualized by a status bar and an indicator light. Both turn yellow after the simulation is completed.
- The program can be stopped at any time by clicking on the stop button  (this will abort the simulation). Resuming the program is possible by using the resume button .

The advanced simulation settings (2nd sensor position and current feed option) are detailed in the example section of this document.

4.1 Results Windows

The bars in Fig. 8 show the calculated differential field (x-field) and the impact on the stabilization field (y-field), based on the specified busbar geometry and the nominal current. In addition, the current density (A/mm²) at the busbar's smallest cross section is calculated in order to estimate, whether thermal effects and power dissipation limits might become an issue. The color of the bars and the current density indicator turn red, if their values are out of target range.

- Differential field: 1920 A/m ±190 A/m
- Impact on stabilization field: 0 A/m ±500 A/m.

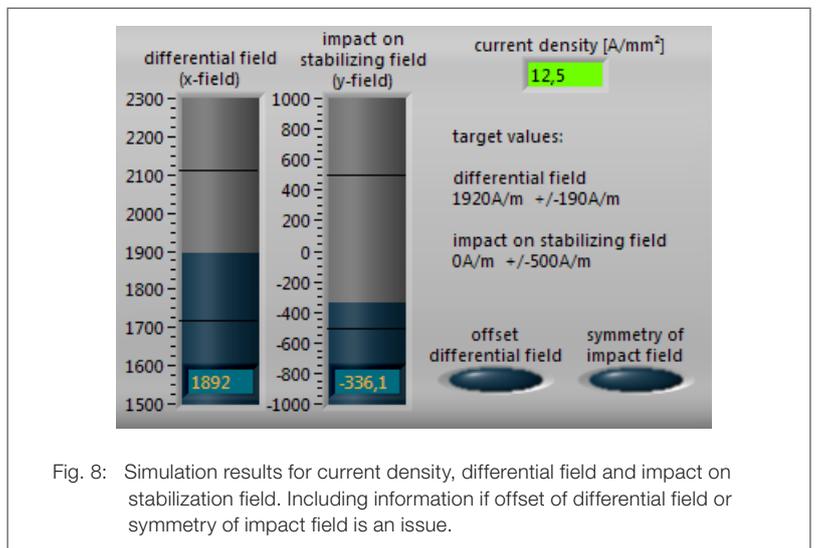


Fig. 8: Simulation results for current density, differential field and impact on stabilization field. Including information if offset of differential field or symmetry of impact field is an issue.

Fig. 9 shows the calculated **differential field** (blue line) and the **impact on the stabilization field** (yellow line). The fields are calculated in a ±1 mm range relative to the sensor's center, whereby the black lines perpendicular to the x-axis mark the base width of the active chip area (1.2 mm). An optimal design is characterized by a differential field about 0 A/m at 0 mm base width (chip center) and ±960 A/m at ±0.6 mm base width (chip edges). In addition, the maximum allowed impact on the stabilization field is supposed to be inside the ±500 A/m range. Small deviations in both fields are still tolerable, but must be verified in the final application.

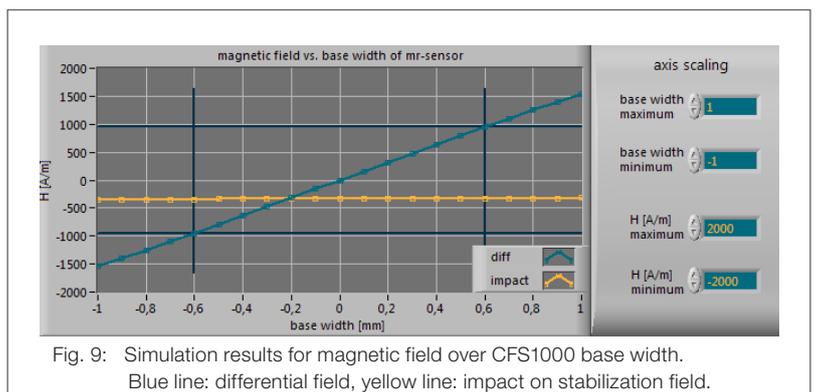


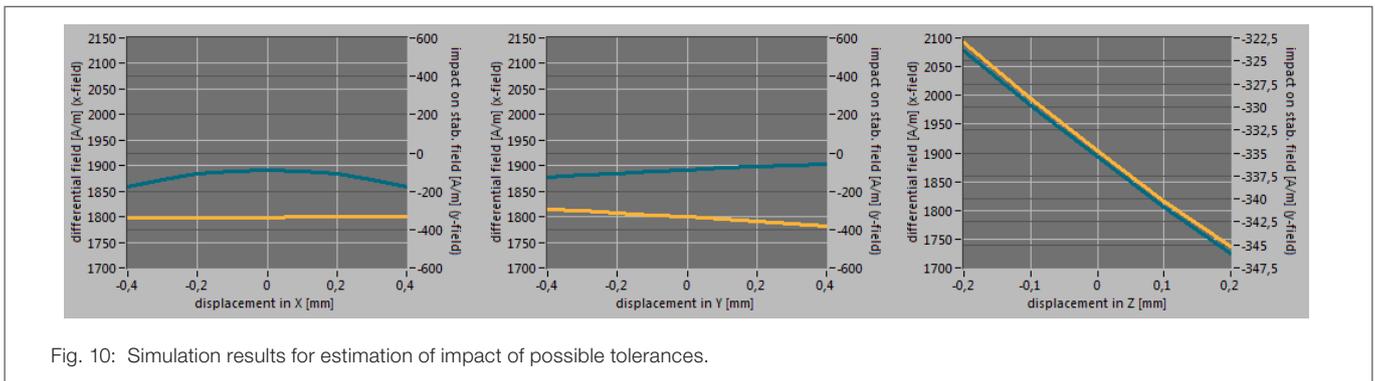
Fig. 9: Simulation results for magnetic field over CFS1000 base width. Blue line: differential field, yellow line: impact on stabilization field.

4.2 Tolerance Views

The influence of sensor placement errors relative to the busbar can be estimated using the tolerance view panel (Fig. 10). Here, the blue line indicates the differential field change and the yellow line the change in impact on the stabilization field, when moving the sensor along the x-, y- or z-axis.

Note:

The scale of the graphs is not fixed, but can be modified manually by clicking on the min/max scale numbers – if required for a more detailed investigation. Scaling is only possible in y-direction.

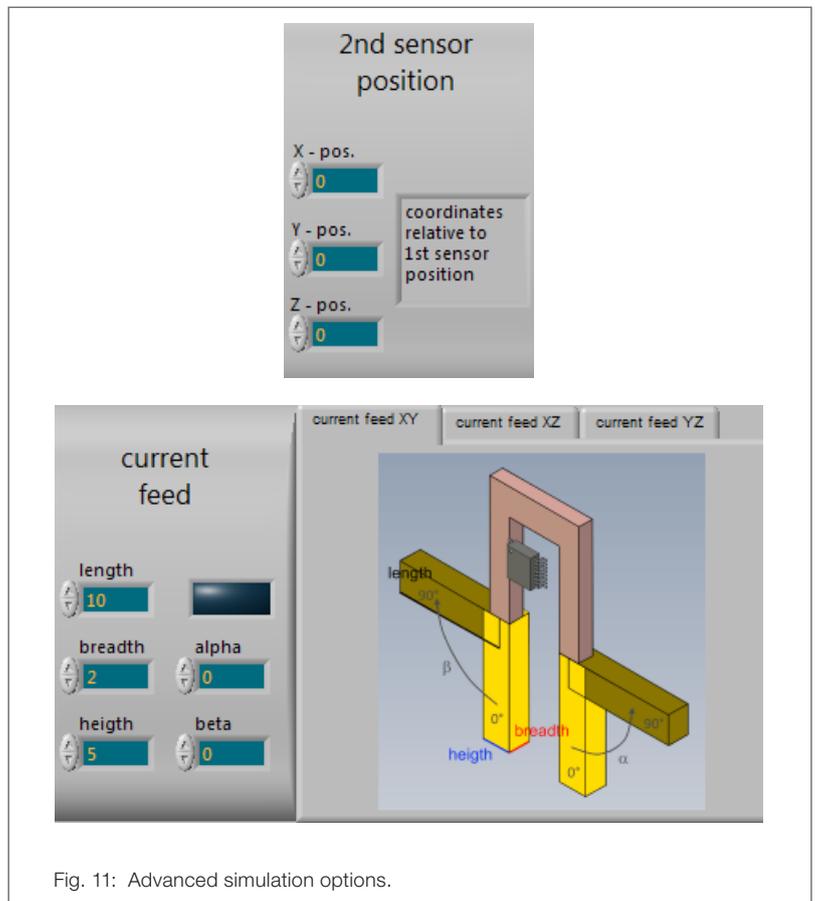


4.3 Advanced Settings

The index-tab advanced settings (see Fig. 6) offers two advanced options (Fig. 11):

- The possibility to add a 2nd sensor for the estimation of crosstalk between adjacent sensor arrangements, whereby the second sensor will be located at the entered coordinates, which are relative to the 1st sensor.
- Definition of current feed, including geometry settings. The left block is used to define dimensions and angles, the illustration on the right-hand side allows to set the orientation (xy, xz, yz) of the current feed of the busbar.

The advanced settings are detailed in the examples section.



5. Examples

This section covers some common cases, which one may encounter during design-in-phase of the CFS1000. All examples clearly show how to use Calc-U-Bar and how to interpret the simulated results. In general, the user must provide the geometry data of the busbar and the isolation layer thickness, as well as the nominal current of the target application.

As additional help, some predefined examples are available by turning on the switch example settings. Typical busbar and setup dimensions for currents from 10 A up to 1000 A are shown (Fig. 12).

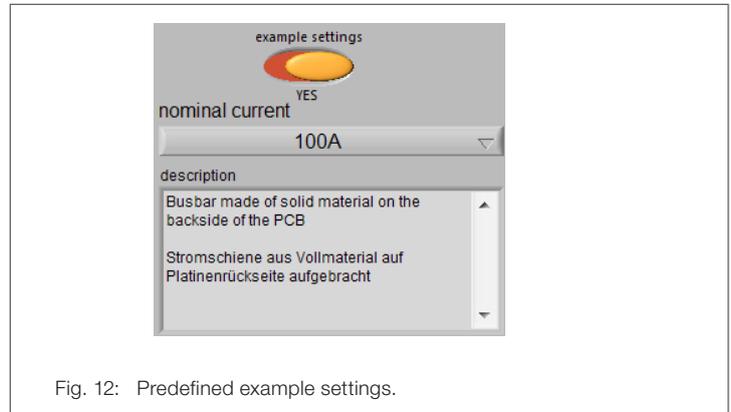


Fig. 12: Predefined example settings.

5.1 External U-shaped Busbar – 100 A

The user must enter the following parameters:

- Thickness 2 mm
- Width1 4 mm
- Width2 5 mm
- Length1 30 mm
- Length2 5 mm
- Gap 2.1 mm
- Distance 1 mm (isolation layer thickness)
- Nominal current 100 A

At this stage, the advanced options current feed and 2nd sensor position should be switched off. The example for 100 A nominal current using an external busbar is shown in Fig. 13.

It represents a compact, low cost system consisting of a CFS1000 mounted on a standard 1 mm PCB with a 2 mm thick busbar fixed to its backside. Such an external busbar-solution is probably a cheaper solution when compared to an expensive high power PCB solution using special copper inlays, which carry the nominal current.

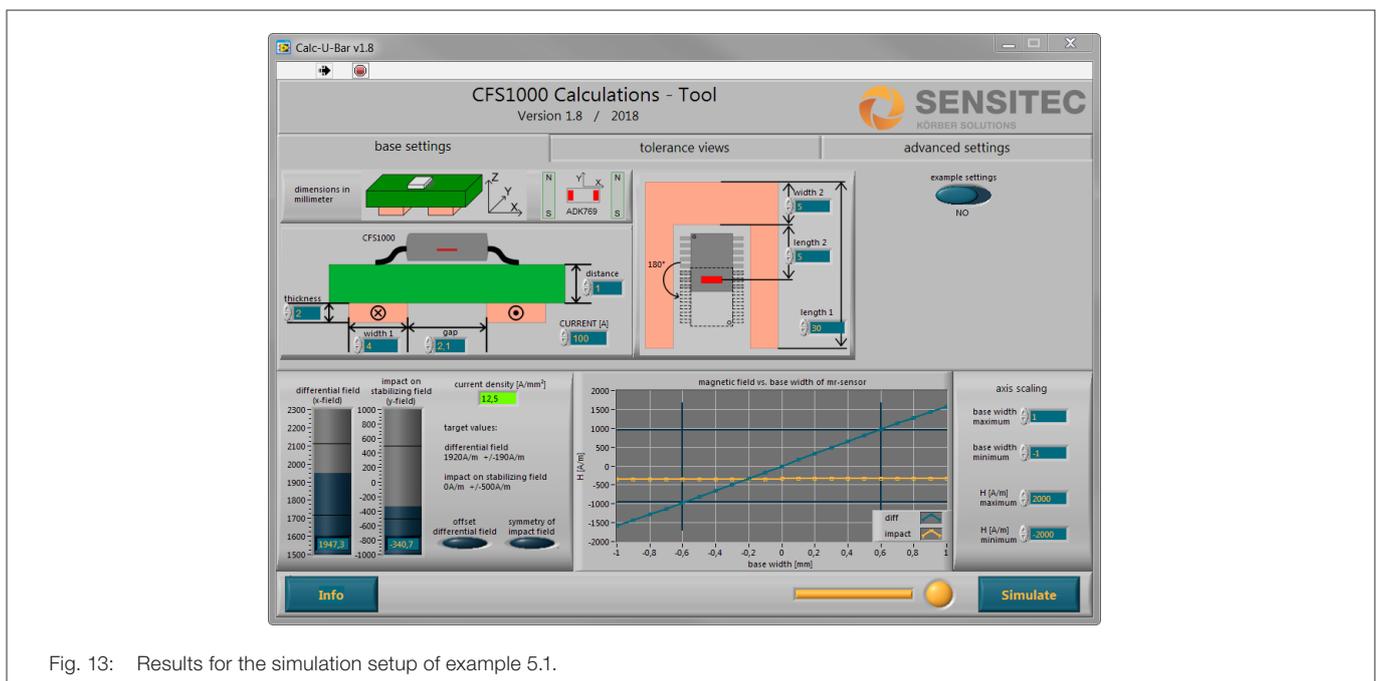


Fig. 13: Results for the simulation setup of example 5.1.

The simulation results offer the possibility to estimate, whether the necessary requirements to safely operate the CFS1000 are met, or not:

- Differential field 1947 A/m OK
- Impact on stabilization field -340 A/m OK
- Differential field at the sensor's center about 0 A/m OK
- Current density 12.5 A/mm² OK

As stated in the beginning, the calculated current density can be used to estimate, if temperature effects may become an issue. In this example, it is controllable and thus, a realistic choice for a low-cost product without the need for active cooling.

Placement Tolerances

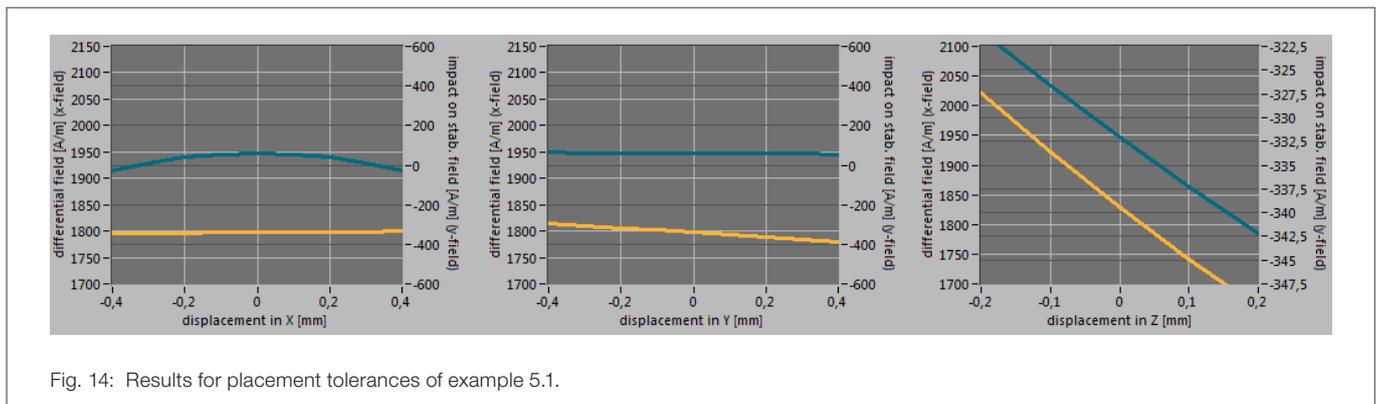


Fig. 14: Results for placement tolerances of example 5.1.

It can be seen that placement errors (± 0.2 mm) in x- and y-direction show only a minor influence on the magnetic field components, contrary to a variation in z-direction (see Fig. 14). The impact on the stabilization field (yellow curve) is only slightly affected and remains below the critical target range of ± 500 A/m. The differential field however, ranges from 1785 A/m to 2125 A/m. This equals a sensitivity change of -8.32% to +9.14% for a distance variation of ± 0.2 mm in z-direction.

In reality, thermal expansion of the PCB might be up to 0.01 mm. So, this graph can be used to estimate gain errors due to thermal drifts, or in other words: When the current sensor arrangement measures 100 A at a busbar temperature of 100 °C this might be a real current of 100.51 A as the PCB has expanded to 1.01 mm. Thus, reducing the differential field from 1947 A/m down to 1938 A/m.

In general, the graphs can be used to estimate if the sensor will operate safely in the presence of placement errors due to process tolerances, or if it may become necessary to run an end-of-line gain calibration inside the final application.

As soon as the calculation results meet the target values, with dimensions suitable for application requirements, the advanced option current feed should be activated. Compared to the simple U-shaped busbar, the position and angle of the current feed can influence the magnetic field at the sensor position noticeably (field symmetry). In most cases, such an influence can be counteracted by changing the sensor position or by varying the length of the U-shaped busbar. Even an asymmetrical current feed can be compensated by placing the sensor slightly out of its centered position (relative to the busbar). Due to this current feed influence, it is not recommended to minimize the busbar space in the first step, but to reserve space for variation instead. Further details on this topic can be found in the following examples of this document.

5.2 U-shaped-Busbar – 250 A

This example shows a design approach for a current measurement arrangement for 250 A nominal current. As shown in Fig. 15, the dimensions need to be considerably larger than for 100 A nominal current, mostly due to higher current density, thermal requirements and larger distance to the CFS1000. The distance was set to 1.6 mm, which is standard PCB value having a copper busbar glued to the backside.

- Thickness 4 mm
- Width1 5.5 mm
- Width2 7 mm
- Length1 30 mm
- Length2 10 mm
- Gap 5 mm
- Distance 1.6 mm (isolation layer thickness)
- Nominal current 250 A

Depending on production technology, the gap of 5 mm might already be a low limit for fabrication of 4 mm thick busbars. Anyway, remember the possibility to use two tracks carrying the same current with opposite direction to generate the differential field. A set of two separate busbars placed in correct distance carrying same current in opposite direction will also bring the same differential field without the need of a space consuming U-shape.

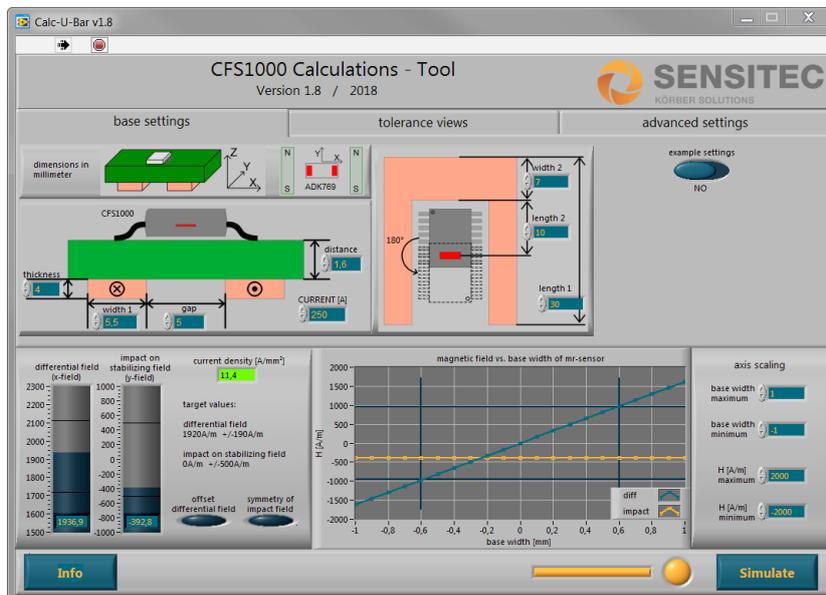


Fig. 15: Results for the simulation setup of example 5.2.

Here, all parameters meet the target ranges, whereby the differential field (1937 A/m) is very close to the target value of 1920 A/m. The field component counteracting the stabilization field with -393 A/m is still inside the allowed range of ± 500 A/m.

In comparison to the tolerance graphs of the previous example, the influence of sensor positioning errors decreases with increasing sensor-system dimensions. That is, the influence of distance variations in z-direction decreases from above 8% in example 1 to roughly 4.5% for a distance tolerance of ± 0.2 mm.

This leads to a general conclusion on the behavior of the CFS1000: The smaller the nominal current, the U-shape and the isolation layer thickness, the stronger the influence of placing tolerances get.

5.3 Current Feed Influence in XY-Plane

Based on the dimensions of example 1 (except for length1, which is now set to 15 mm), the influence and calculating capabilities of Calc-U-Bar – regarding current feed from different directions – is explained. To simulate the most common case of a U-shaped busbar with straight current feeds from both sides, the switch „current feed“ (advanced settings) has to be activated and the sub-index-tab „current feed xy“ must be chosen.

- Length 100 mm
- Breadth 2 mm
- Height 7 mm
- Alpha 90°
- Beta 90°

Fig. 16 shows the corresponding simulation results with both angles set to 90° and equal breadth of 2 mm. The current flow is from the left side of the busbar to the right side.

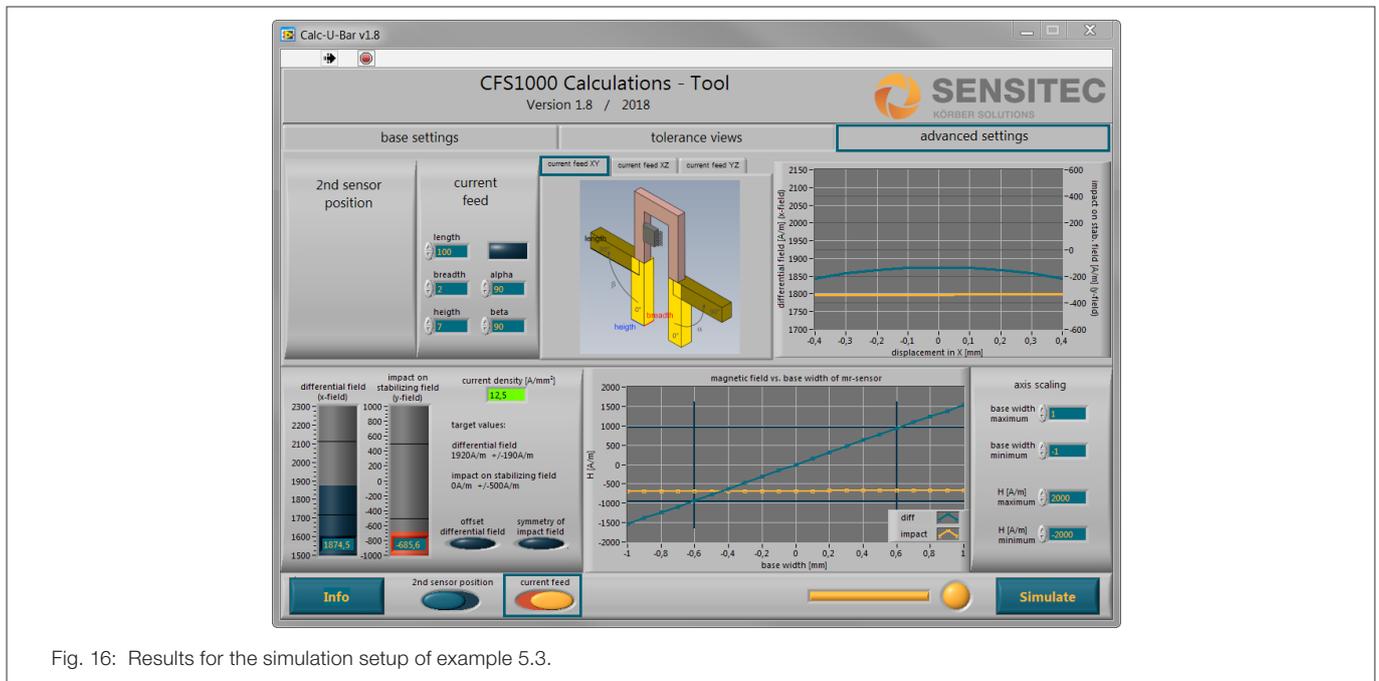


Fig. 16: Results for the simulation setup of example 5.3.

In comparison to example 1, there is only a minor change in differential field, but the impact on the stabilization field has increased from -340 A/m to -685 A/m, which is out of range now. Hence, overcurrent-stability should be focused on during first performance tests. It can be concluded that, using such a busbar setup will generally have an impact on the stabilization field. In reality, the differential field is expected to be affected as well (even though in a small manner), due to an inhomogeneous current distribution inside the busbar, which will create an inhomogeneous magnetic field at sensor position. Calc-U-bar will not consider such effects, as it generally assumes a homogenous current density inside the busbar.

To avoid too large errors regarding this issue, a 3D FEM-simulation should be considered as soon as dimensions for current feed height and U-shape length bring the upper corner of the current feed too close to the CFS1000. As soon as the shortest path (least ohms) allows current flow in an angle α larger than 10° (Fig. 17), the calculation error will increase above 2%. In addition, the current connection concept will become crucial, if the busbar thickness (z-direction) increases above 10 mm.

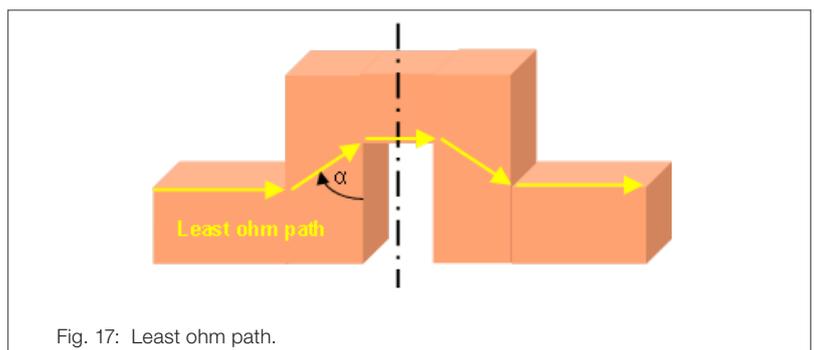


Fig. 17: Least ohm path.

5.4 Current Feed in XZ-Plane

In this example a current feed position, which might be relevant when having connections/terminals adjacent to the sensor position, is simulated. The basic busbar geometry and nominal current settings can be found in example 1. Figure 18 shows the current feed settings (current feed xz) and the related simulation results.

- Length 100 mm
- Breadth 4 mm
- Height 2 mm
- Alpha 180°
- Beta 180°

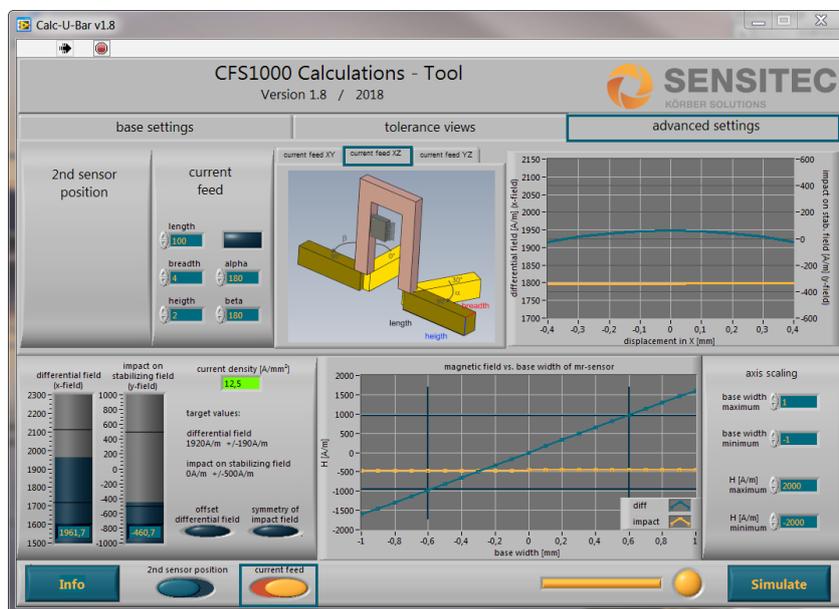


Fig. 18: Results for the simulation setup of example 5.4.

The differential field is about 1961 A/m and the impact on the stabilization field about -460 A/m. Both parameters are within the target range.

5.5 Current Feed in YZ-Plane

The third possibility to vary the current feed direction is a change of angle in the yz-plane. The basic busbar geometry and nominal current settings can be found in example 1. Figure 19 shows current feed settings and the related simulation results.

- Length 100 mm
- Breadth 2 mm
- Height 4 mm
- Alpha 90°
- Beta 0°

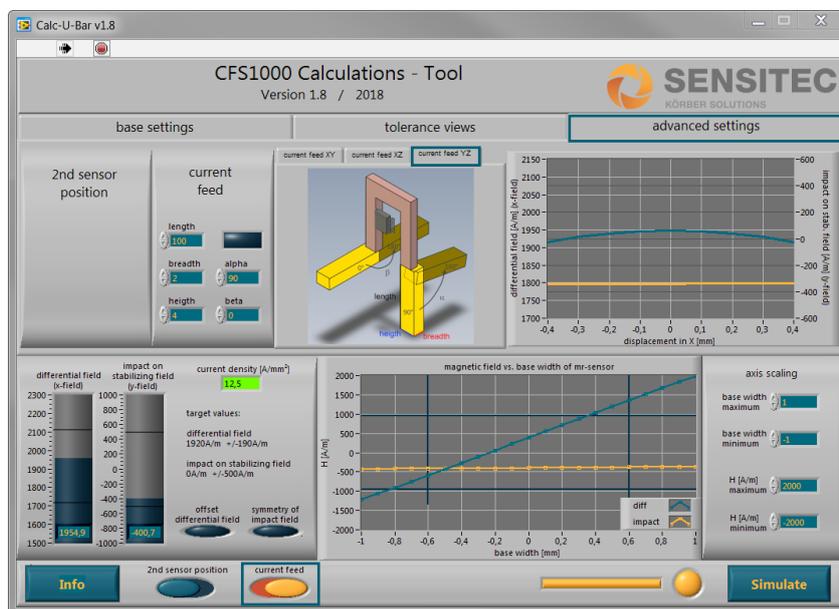


Fig. 19: Results for the simulation setup of example 5.5.

Due to the missing symmetry, the differential field shows an offset of about 400 A/m in the center of the sensor chip area. Anyway, the differential field is still within the target range. The impact on the stabilization field can be observed by scaling the y-axis accordingly (max -350 A/m and min -500 A/m). Its difference between the edges of the sensor chip area is about 40 A/m, due to the asymmetry of the busbar. In such cases, a rework of busbar dimensions and chip placing can help to overcome these issues. Otherwise stable operation in overload situations and linearity should at least be tested as soon as hardware is available.

5.6 Phase Crosstalk: 2 Adjacent CFS1000 Sensors

Calc-U-Bar also offers the possibility to investigate if crosstalk, coming from adjacent current paths, may be an issue for the CFS1000. This is of great help when operating the sensor in a highly integrated system where multiple high current paths are close to each other.

To calculate phase crosstalk, fill in all necessary parameters like busbar geometry and nominal current and turn on the switch “2nd sensor position” under index-tab advanced settings. Calc-U-Bar then calculates the influences of the magnetic field, generated by phase 1, towards the 2nd sensor, whose position is to be defined using the coordinates in the dimension input boxes. The coordinates for the second sensor are relative to the origin of the first sensor position.

Case 1:

The second CFS1000 sensor to be influenced is moved only in y-direction in this example. The example represents a two phase arrangement with identical busbars for 250 A, whereby busbar #1 (CFS1000 #1) carries 250 A and busbar #2 (CFS1000 #2) carries no current. Therefore, CFS1000 #2 will be influenced by the magnetic field of busbar #1. Calc-U-Bar calculates both the impact on the differential field and the impact on the stabilization field (Fig. 20). The base settings are taken from example 2, whereby the second sensor is placed in +50 mm distance in y-direction.

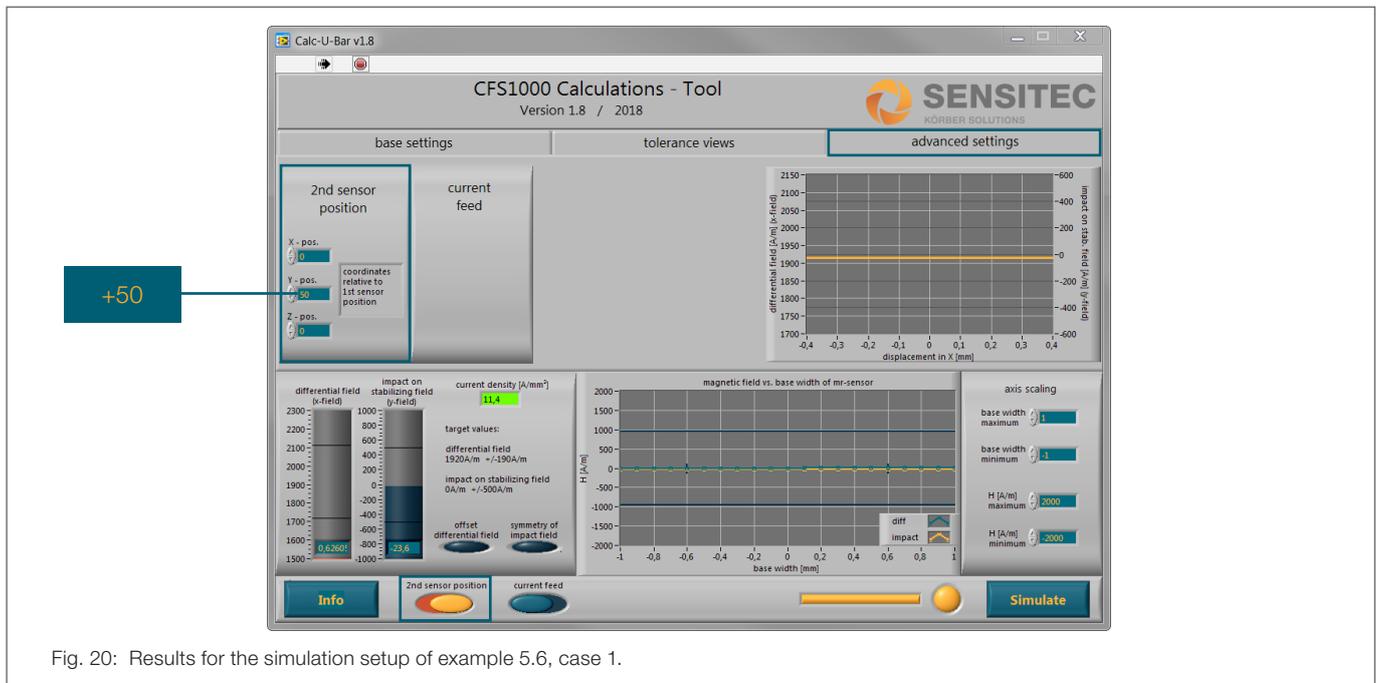


Fig. 20: Results for the simulation setup of example 5.6, case 1.

In this example, the influence is quite small. The differential field of sensor #2 is almost not affected (0.62 A/m) and the impact on the stabilization field is about -23.6 A/m. In this case, the crosstalk is small and therefore, does not threaten proper sensor operation.

Even if the crosstalk is quite small regarding the differential field, care has to be taken in order to avoid a too large differential field offset (may not exceed ± 500 A/m). Such an influence may modulate the characteristic curves of the CFS1000 leading to errors up to 1% in the presence of stray fields and/or symmetry related field offset about ≥ 1000 A/m. Offset is the field value at position 0 mm in graph „magnetic field vs. base width of mr-sensor“. A high offset coming from another stray field source will not only cause error in size of its gradient field, but also lead to decreased compensation capability of the sensor, which can cause additional linearity errors. By varying the position of the second sensor element, the minimum spacing for multiphase arrangement can be found regarding the sensors maximum allowed mutual influence on the differential field.

Note that all spacing and production tolerances still have to be taken into account.

Case 2:

Busbar #2 (CFS1000 #2) carries 250 A and busbar #1 (CFS1000 #1) carries no current. Therefore, CFS1000 #1 will be influenced by the magnetic field of busbar #2. This operation can easily be performed by inverting the sign of the y-position coordinate (Fig. 21).

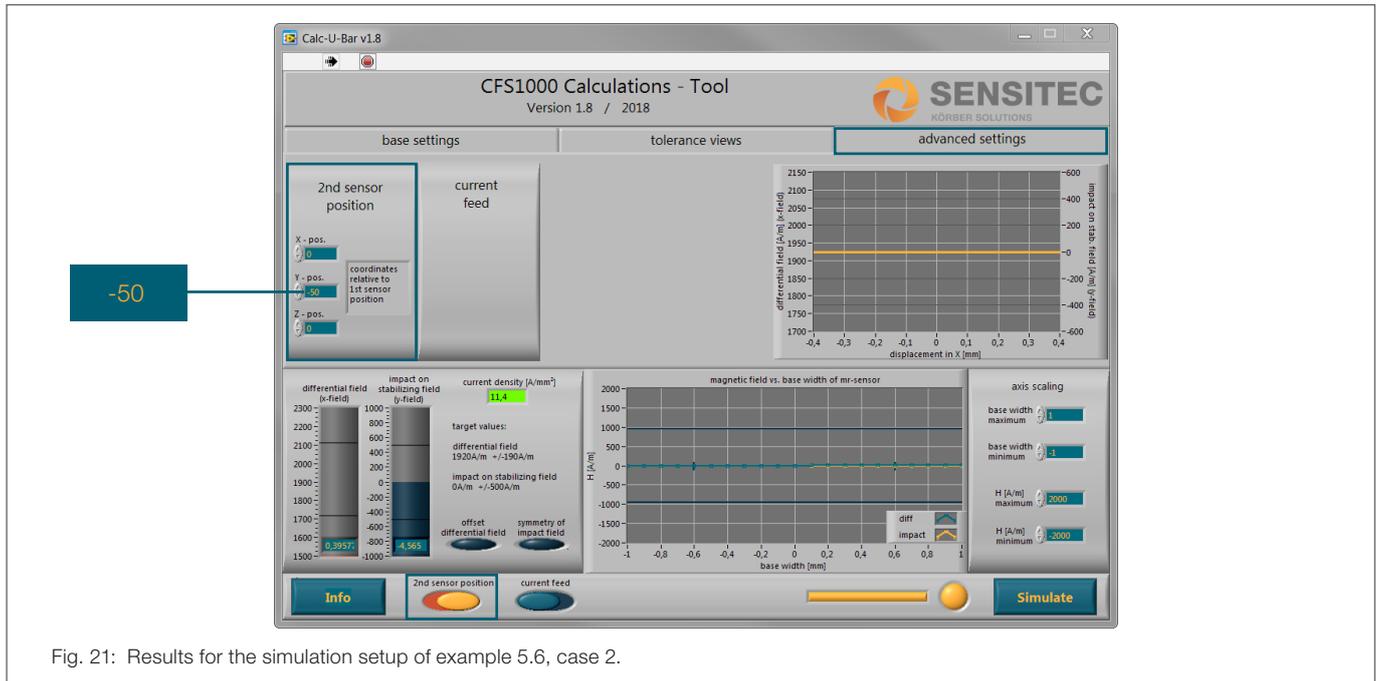


Fig. 21: Results for the simulation setup of example 5.6, case 2.

The differential field of sensor #1 is almost not affected (0.39 A/m) and the impact on the stabilization field is about -4.56 A/m. The crosstalk is small and therefore, does not threaten proper sensor operation.

In general, the additional impact – due to crosstalk – may cause problems as soon as both paths carry an overcurrent in the same direction, i.e. sensor fails due to the breakdown of the stabilization field. However, in most standard applications multiphase arrangements work with AC currents having a 120° phase shift, so that the additional impact is not a matter. Nevertheless, under uncertain conditions it is recommended to increase the distances between the sensors in order to guarantee correct device operation.

Note: For multiphase AC arrangements, care must be taken to check also the influence of phase angle, which has to be transformed to a current value for one moment in time for each case of interest.

5.7 PCB with Integrated Current Path: 50 A in PCB

Also designs where the current path is integrated into the PCB can be simulated. Not only heavy copper inlays, but also multilayer current routes can be designed and investigated applying a simplified model. Methods, simplifications and rules that are helpful for this task, are discussed in the following. There are two general strategies for calculating the differential field of a current path which is separated to several layers in a multilayer PCB.

1. Estimate the current for each layer, calculate the generated differential field for each layer and sum all the calculation results afterwards.
2. Assume all layers – similar geometry required – as one block of copper, whereby for coil windings in multiple layers, the current has to be multiplied by the number of windings.

Starting point is a setup for a 50 A busbar (Fig. 22), applying standard PCB design rule constraints. The calculated results are assumed to be valid also for a multilayer PCB, where the current spreads to several different layer.

A 4-layer 100 µm copper path was chosen for the primary current. The thickness was set to 0.7 mm, assuming a stack of 4 copper layers (100 µm each) and 3 isolating prepreg layers (100 µm each). For simulation, the stack is simplified to one massive copper busbar as the current is assumed to flow equally through all 4 parallel connected layers. In order to provide sufficient isolation and shielding, the isolation layer thickness was set to 0.55 mm – as most applications require an isolation layer thickness of at least 0.5 mm for FR4-material. The other parameters are:

- Thickness 0.7 mm
- Width1 3.6 mm
- Width2 5 mm
- Length1 13 mm
- Length2 4 mm
- Gap 0.3 mm
- Distance 0.55 mm (isolation layer thickness)
- Nominal current 50 A

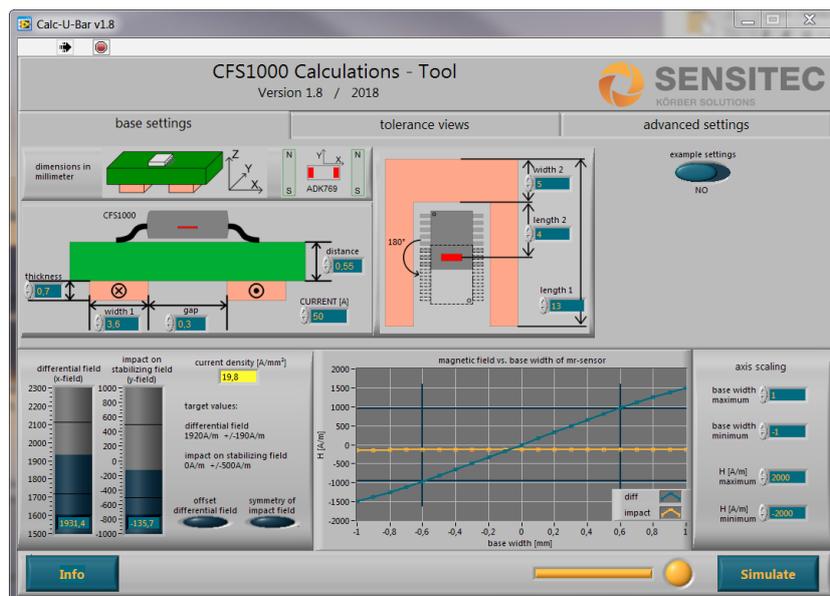


Fig. 22: Results for the simulation setup of example 5.7.

In this example, the current density is calculated to 19.8 A/mm^2 , which may require some special attention regarding thermal topics. Since the target differential field is only required directly at the sensor position, it is possible to enlarge the nominal-current-layers in a distance of about 10 mm, relative to the sensor position, to compensate local heat generation.

For further improvement of the model it would be another alternative strategy to evaluate the resistance of each layer connection separately and to calculate the resulting currents for each one. Then, the exact field portion of each layer can be calculated separately and summed afterwards. Especially the layer with the closest distance to the sensor represents a risk for dimensioning errors, if not interconnected properly with vias to the main connection layer (usually top or bottom layer). Calc-U-bar allows dimension variation with a resolution down to $1 \mu\text{m}$ for this purpose.

Note:

Current spreading to different layers will produce effects like higher current density at the lowest resistive path. However, this is assumed to be negligible in this simplified investigation. In general, PCB designing will require a sufficient number and size of vias and copper thickness to guarantee required current-carrying capability and to avoid thermal issues. Additional heat spreading layers without direct connection to the circuit may also help to spread heat generated from local hot spots, but should be interrupted to prevent eddy currents during switching events. One should keep in mind that, a standard thickness tolerance can be around 10%, which will affect the final result.

5.8 PCB with Integrated Current Path: 10 A Coil in PCB

The task is to design a coil with several windings sufficient to achieve the target value for the differential field at 10 A nominal current. The same layer settings with 100 µm copper and 100 µm prepreg, as presented in example 7, were chosen. Fig. 23 shows the simulation results.

The coil is simplified by a single massive copper busbar. Six windings are required to achieve the target differential field, which means that the target value for the nominal current is scaled by a factor of six. Thus, not only thickness, but also the copper width (width1) and the primary current have to be changed, with respect to layer setup and layout design rules, in order to get an approximated model for coil geometry.

In this example, we apply a 2-layer coil setup with three windings in each layer, a route width of 1.66 mm and a distance of 0.2 mm between two windings.

- Thickness 2 times 100 µm copper + 100 µm FR4 = 0.3 mm
- Width1 3 times 1.66 mm route + 2 times 0.2 mm spacing = 5.4 mm
- Width2 7 mm (at least equal to width1)
- Nominal current 2 layers · 3 windings · 10 A = 60 A

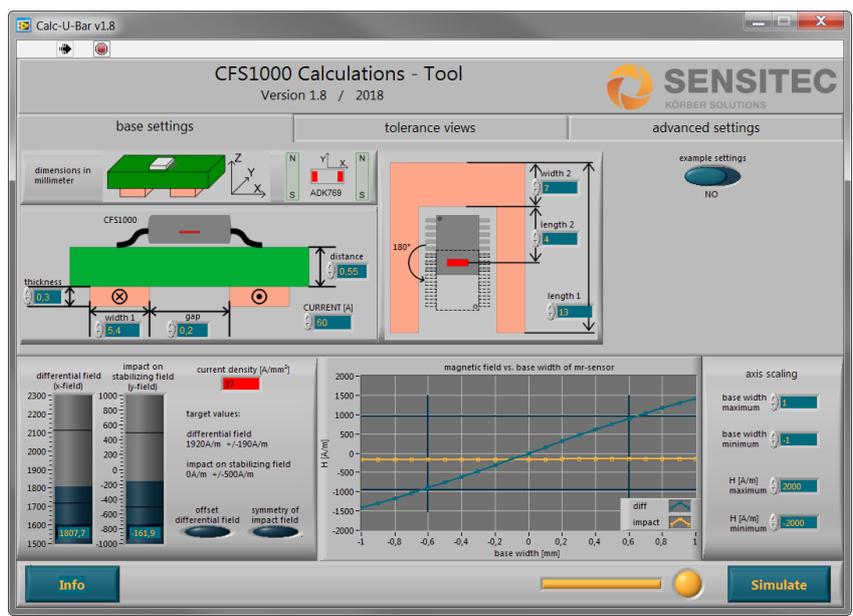


Fig. 23: Results for the simulation setup of example 5.8.

Note:

The influence of the windings can't be calculated by Calc-U-Bar. However, the impact field components coming from the returns will cancel or at least weaken each other anyway – as long as the sensor element (between Pin 7 and Pin 10 of the CFS1000) is placed close to the center of the coil.

The simulation result might be improved, when calculating the differential field portion of each single winding separately, including a summation afterwards. In this case, it is even easier compared to example 7, because the current for each path is known and equal. Nevertheless, for such arrangements, placing tolerances, especially towards closest winding of the coil, become more critical as distances become smaller. For such complex arrangements a prototyping test or 3D FEM-simulation is strongly recommended.

The best solution when using a PCB integrated coil, is to place the vias in a short distance of the package side between Pin 8 and Pin 9. This is easiest solution to maintain creepage requirements for safe isolation. Fig. 24 shows two interconnection methods for such arrangements.

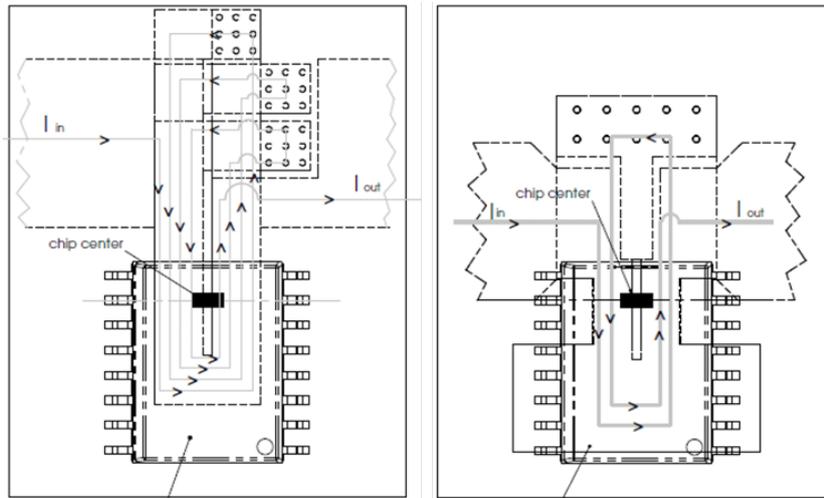


Fig. 24: Different interconnection methods for PCB integrated current paths.

6. Limitations of Calc-U-Bar

Calc-U-Bar is a customer support tool aiming at simple feasibility studies. It is not supposed to be used for designing series products. Therefore, the reader is kindly asked to carefully read through the following limitations of the tool. It does not take into account:

- Inhomogeneous current distributions, which will influence the differential field. For example due to a narrowing of the current path's cross sectional area close to the sensor position
- Eddy current effects, such as the skin effect. The same applies for proximity effects
- Thermal effects like local hot spots, due to higher current densities at the current path's corners
- Mechanical effects
- Isolation topics

For a more advanced investigation, a 3D FEM-simulation is of great advantage, since it will cover all the previously mentioned aspects. Additionally, it is possible to:

- Design shielding or flux guiding metals, in order to improve the stray field immunity and the influence towards the stabilization field
- Reduce the total system size by optimizing the busbar geometry based on highly accurate simulation results
- Transform the current pulse into a field pulse, which can be used as SPICE model input in order to evaluate the dynamic performance of the CFS1000 assembly

Sensitec is able to cover all these aspects and to provide an advanced engineering support. Please contact the Sensitec sales department for more information.

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