



INSPIRED ENGINEERING

CURRENT SENSORS

REFERENCE DESIGN GUIDE

Application Note

This document describes several reference designs for current sensing applications with either conventional or planar IMC-Hall® sensors. The design solutions cover various current ranges (from 2 to 2000A) and conductor types (bus bar, PCB, cable). Also included is a quick selection guide for Melexis Hall effect current sensors, general magnetic design guidelines and information on ferromagnetic materials.

TABLE OF CONTENTS

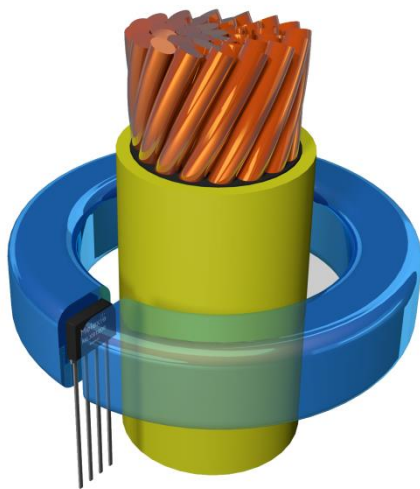
CURRENT SENSOR TYPES.....	3
CONVENTIONAL HALL SENSORS.....	3
PLANAR IMC-HALL® SENSORS.....	3
CONVENTIONAL HALL SENSORS.....	4
1.1 MAGNETIC DESIGN	5
1.1.1 Examples	5
1.2 QUICK SELECTION GUIDE	6
1.2.1 Main features	6
1.2.2 Option code and sensitivity range	6
PLANAR IMC-HALL® SENSORS	7
2.1 IMC VERSIONS.....	8
2.2 MAGNETIC DESIGN	9
2.2.1 Magnetic field estimation (with shield).....	9
2.2.2 Magnetic field estimation (without shield).....	10
2.2.3 Dimensioning examples.....	11
2.2.4 Conductor with neck-down.....	11
2.2.5 Shield design for very high currents.....	12
2.2.6 Canceling stray field without shield.....	12
2.2.7 Avoiding cross-talk without shield.....	12
2.3 QUICK SELECTION GUIDE	13
2.3.1 Main features	13
2.3.2 Option code and sensitivity range	13
2.4 PCB DESIGN: GUIDELINE	14
2.5 REFERENCE DESIGNS.....	15
2.5.1 PCB application, 2-10A range, multi-layer/multi-turn solution	16
2.5.2 PCB application, 2-10A range, ferromagnetic shield solution.....	17
2.5.3 PCB application, 10-50A range.....	18
2.5.4 Bus bar application, 50-250A range	19
2.5.5 Bus bar application, 300-700A range	20
2.5.6 Bus bar application, dual range 5A/200A.....	21
2.5.7 Cable application, 10-100A range	22
FERROMAGNETIC MATERIALS.....	23
3.1 SUPPLIERS	23
3.2 FERROMAGNETIC SHIELDS	23
3.2.1 Standard U-Shield.....	23
3.2.2 Mechanical assembly	24
3.3 FERROMAGNETIC CORES	25
END-OF-LINE CALIBRATION.....	26
3.4 INTRODUCTION	26
3.5 DIRECT SENSOR CALIBRATION.....	26
3.6 MICRO-CONTROLLER LEVEL CALIBRATION.....	26
ADDITIONAL INFORMATION.....	27
CONTACT US.....	27

Current sensor types

Melexis provides two types of current sensors suitable for a broad range of applications.

Conventional Hall sensors

These current sensors are sensitive to the magnetic field **perpendicular** to the chip surface. They are meant to be used in combination with a ferromagnetic core. In a typical application, the core is wrapped around the current-carrying conductor and concentrates the magnetic flux on a small air gap (typically 2-5mm) where the sensor is inserted.



Pros

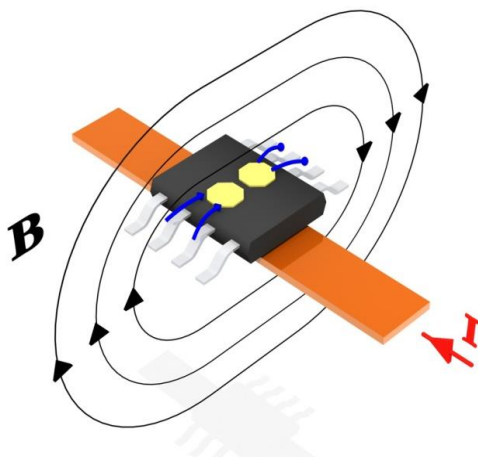
- Strong magnetic gain from the core
- Very robust against cross-talk
- Suitable for medium to very high currents

Cons

- Performance limited by the core (geometry and material): saturation, hysteresis, frequency response and thermal drift
- Bigger footprint (size, weight) than solutions based on IMC-Hall® sensors

Planar IMC-Hall® sensors

Thanks to the patented integrated magnetic concentrator (IMC) technology, IMC-Hall® sensors are sensitive to magnetic fields **parallel** to the chip surface. Thus, the sensors can directly measure the current flowing in a bus bar or a PCB trace below the package, without the need for a core.

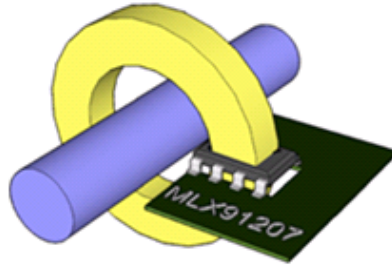


Pros

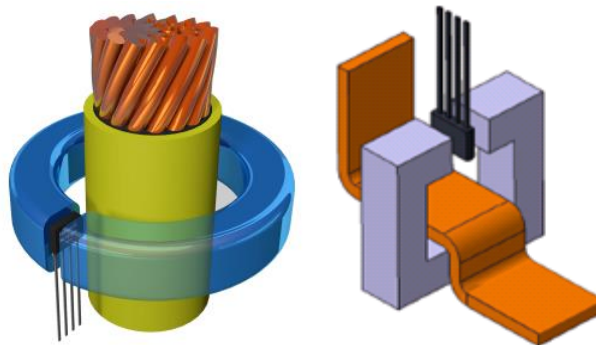
- Sensitive to magnetic field parallel to the chip surface, for easy integration and low footprint
- IMC is made of amorphous magnetic material featuring very high permeability and very low hysteresis
- Magnetic gain from IMC

Cons

- Requires magnetic shielding or specific design to avoid cross-talk and/or noise from external fields

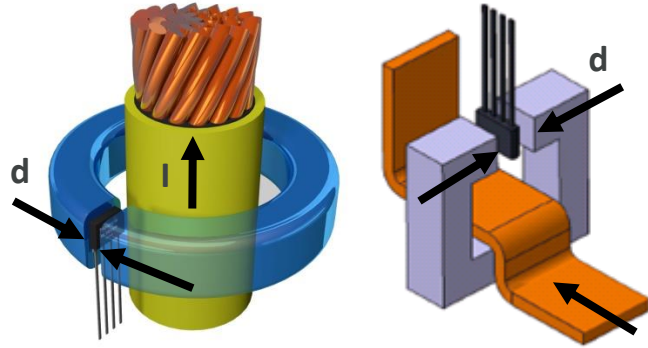


Conventional Hall Sensors



1.1 Magnetic design

For this type of application, the sensor is typically enclosed in the air gap of a ferromagnetic core (ring or square), wrapped around the current-carrying conductor.



The magnetic field at the sensor position (in the center of the air gap), for a current I and a ferromagnetic core with air gap d , can be approximated as:

$$B \text{ [mT]} = 1.25 \cdot \frac{I \text{ [A]}}{d \text{ [mm]}}$$

Equation 1: Magnetic field estimation formula (**with core**).

1.1.1 Examples



MLX91207 DVK core A

$$B@100A = 1.25 \times 100 \text{ [A]} / 1.68 \text{ [mm]} = 74.4 \text{ [mT]}$$

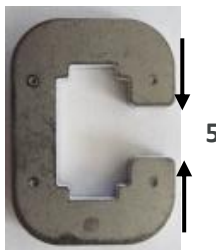
$$\text{required sensor sensitivity: } S = 2000 \text{ [mV]} / 74.4 \text{ [mT]} = 26.9 \text{ [mV/mT]}$$



MLX91207 DVK core B

$$B@200A = 1.25 \times 200 \text{ [A]} / 3.5 \text{ [mm]} = 71.4 \text{ [mT]}$$

$$\text{required sensor sensitivity: } S = 2000 \text{ [mV]} / 71.4 \text{ [mT]} = 28 \text{ [mV/mT]}$$

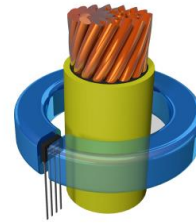


Maglab C-core

$$B@500A = 1.25 \times 500 \text{ [A]} / 5 \text{ [mm]} = 125 \text{ [mT]}$$

$$\text{required sensor sensitivity: } S = 2000 \text{ [mV]} / 125 \text{ [mT]} = 16 \text{ [mV/mT]}$$

1.2 Quick Selection Guide



1.2.1 Main features

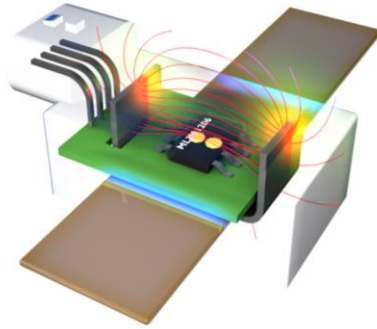
	91207	91209
Sensitivity [mV/mT] <i>*programmable</i>	5-45*	5-150*
Thermal sensitivity drift [ppm/°C]	±150	±150
Thermal offset drift [mV]	±20	±10
Non-linearity [%F.S.]	±0.5	±0.5
Response time [μs]	8	3
Bandwidth [kHz]	100	250
Analog output	Yes	Yes
PWM output	Yes	No
Programmable	Yes	Yes
Diagnostic functions		
▪ Over/Under-voltage detection	Yes	Yes
▪ Broken-track detection	Yes	No
▪ Clamping	Yes	No
Package	SOIC-8	VA (SIP)
Temp. range [°C]	-40-125	-40-150

Table 1: Main features and specifications of conventional Hall effect current sensors.

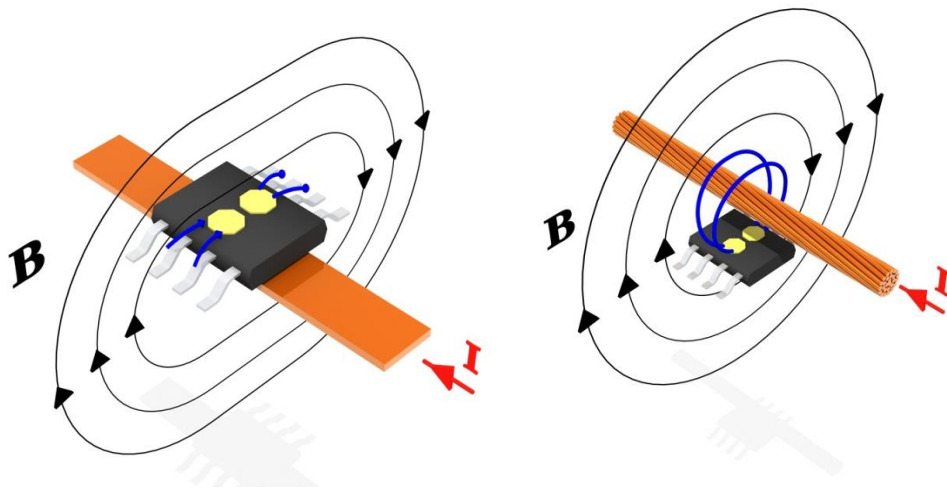
1.2.2 Option code and sensitivity range

Sensor	Option code	Sensitivity range [mV/mT]
MLX91207	CAA-005	15-45 (25)
	CAA-007	5-20 (10)
MLX91209	CAA-001	5-150 (50)

Table 2: Option code and sensitivity range of conventional Hall effect current sensors.



Planar IMC-Hall® Sensors



2.1 IMC versions

IMC-Hall® sensors are available in 3 different versions/sizes (LF, HF and VHF) covering a broad range of sensitivities and magnetic field ranges. With its strong magnetic gain, the biggest IMC (LF) is ideally suited for applications with low currents, requiring high magnetic sensitivities (up to 700mV/mT). At the other end of the scale, the smallest IMC (VHF) can linearly sense strong magnetic fields up to ± 60 mT, for current sensing applications with very high power densities.

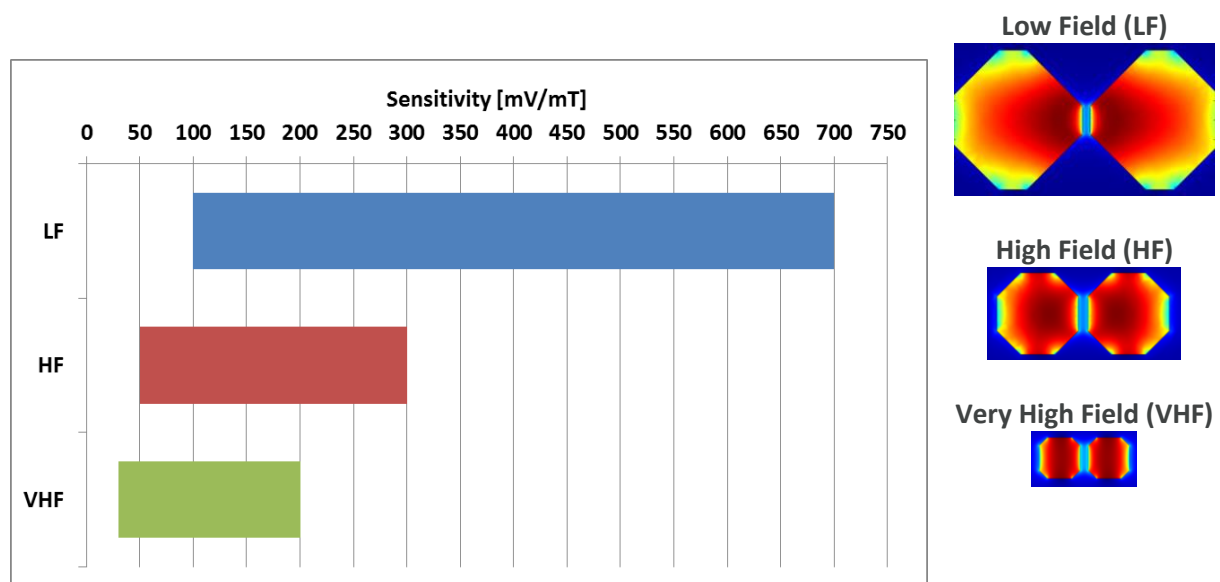


Figure 1: Sensitivity range of each IMC version.

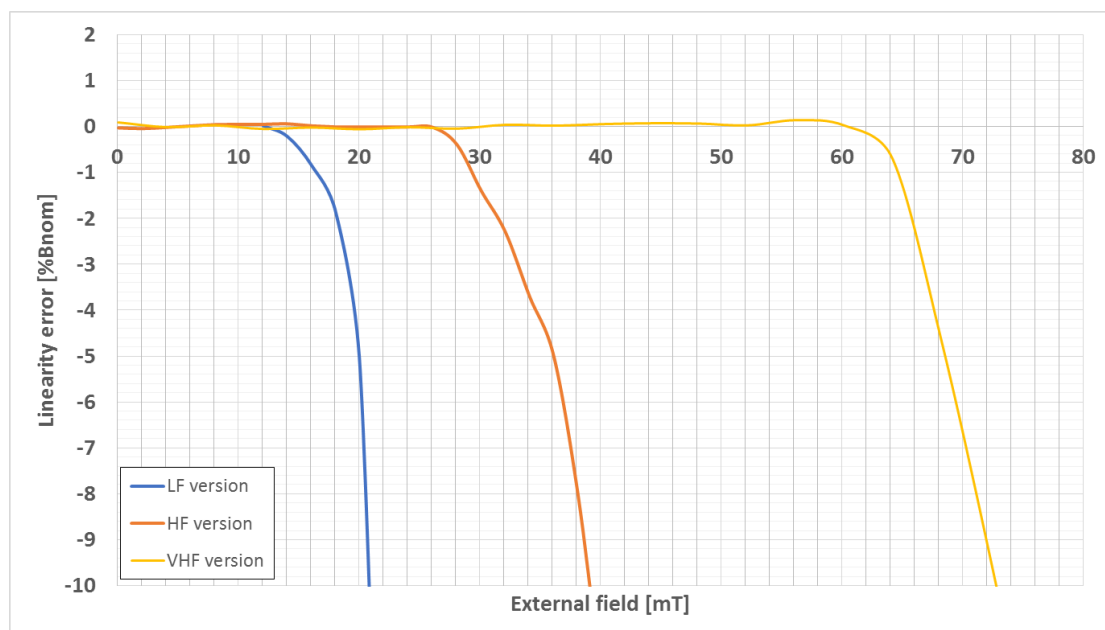
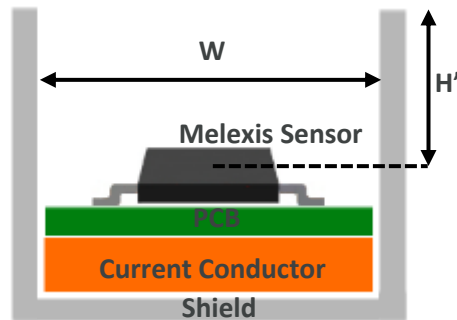


Figure 2: Linearity error [μ T] vs. magnetic field [mT].

2.2 Magnetic design

2.2.1 Magnetic field estimation (with shield)

In a typical application, a U-shaped ferromagnetic shield is wrapped around the current conductor to protect the sensor from external fields and improve the overall robustness of the sensing solution.



The most important dimension of the shield is the inner width. In this configuration, the magnetic field seen by the sensor for a current I and an inner width W can be estimated as:

$$B [mT] = 1.25 \cdot \frac{I [A]}{W [mm]}$$

Equation 2: Magnetic field estimation formula (**with shield**).

The current in the current conductor is generating a magnetic field around it. The ferromagnetic shield will guide the magnetic field lines such that a homogeneous magnetic field is generated in the U-shield between the two legs of the shield, as it is shown in Figure 3.

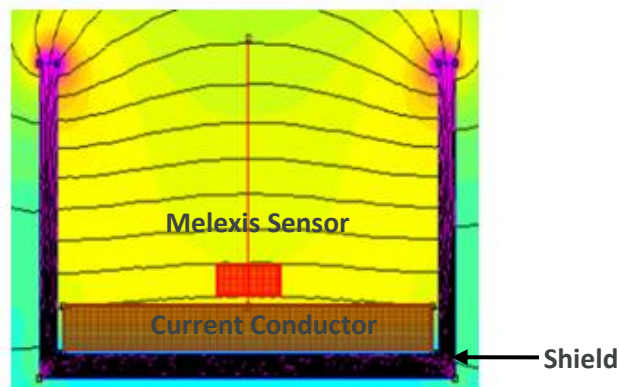


Figure 3: Magnetic field lines distribution in a typical application

Based on these considerations, the following magnetic design rules are essential in order to insure optimal performances:

1. The current sensing module should respect the Ferromagnetic Shield – Current Conductor – Melexis Sensor order of components.
2. In order to have an increased signal-to-noise ratio and for the sensor to see a homogenous field, it should be mounted well inside the opening of the shield, where the field lines are quasi-parallel to each other (the field is homogeneous). One **rule of thumb** is that the

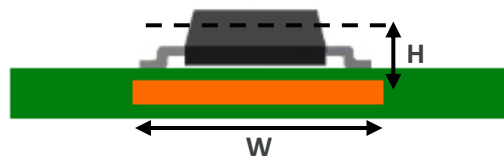
distance from the sensor to the upper side of the shield (H') should be higher or equal to half the width of the shield (W):

$$H' \geq \frac{W}{2}$$

Typically, the shield thickness ranges between 0.8 and 1.5mm (proportional to current range). The height and depth are between 12 and 15mm, in order to properly surround the sensor in each direction. The recommended material is 50%NiFe (Supra50).

2.2.2 Magnetic field estimation (without shield)

Depending on application environment and requirements, the ferromagnetic shield is not necessarily required.



Without shield, the magnetic field seen by the sensor for a current I , a trace width W and a vertical position H can be approximated as:

$$B [mT] = 1.25 \cdot \frac{I [A]}{2 \cdot (W + 2H) [mm]}$$

Equation 3: Magnetic field estimation formula (**without shield**).

2.2.3 Dimensioning examples

The table below provides suggested system dimensions for various current ranges, based on a typical design with a sensor on top of a straight bus bar surrounded by a U-shaped ferromagnetic shield. These dimensions can be easily scaled up or down for higher or lower currents according to the magnetic field estimation formula provided above.

Current [A] (peak)	Shield geometry		Magnetic Field [mT] (peak)	Sensor	
	Width [mm]	Thickness [mm]		Version	Sensitivity [mV/mT]
250	12	0.8	25	HF	80
500	12	1.5	50	VHF	40
1000	25	1.5	50	VHF	40

Table 3: Typical system dimensions.

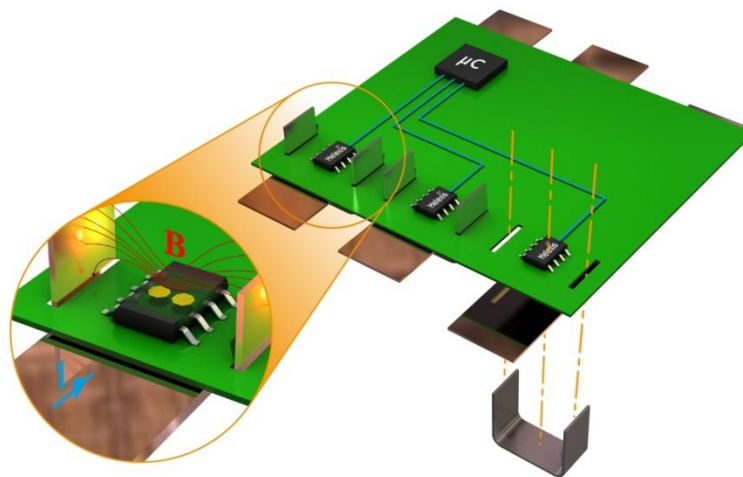


Figure 4: Example of 3-phase inverter current sensing solution with IMC-Hall® sensors.

2.2.4 Conductor with neck-down

In order to limit the cost, size and weight of the shield on systems with wide bus bars, we recommend reducing the cross-section locally, as illustrated on the example below. Such a neck-down has minimal impact on the electrical resistance and allows for a much more compact current sensing solution.

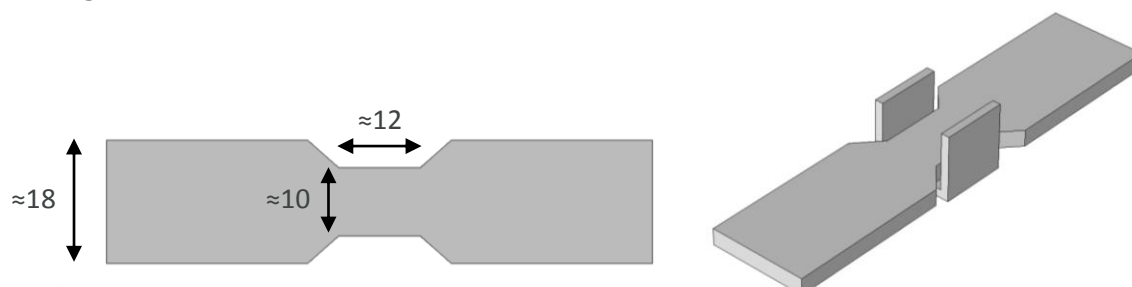
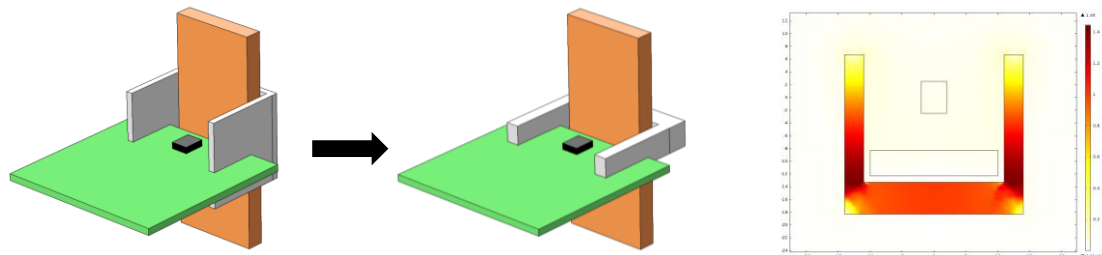


Figure 5: Necked-down bus bar illustration.

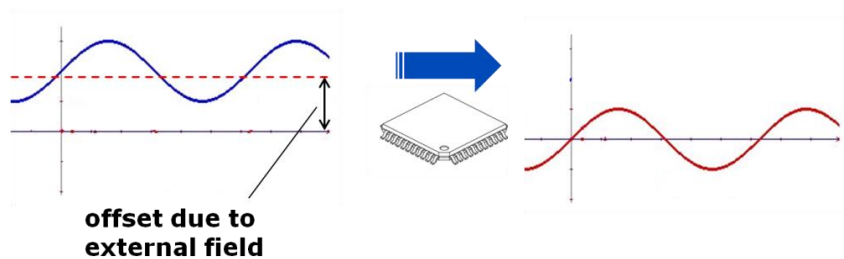
2.2.5 Shield design for very high currents

For very high currents (typically above 800A), instead of the usual single sheet bent to form a “U”, it is often more efficient and cost-effective to use a laminated shield (made of a stack of thin sheets). That way, the in-plane thickness can be increased while decreasing the depth and overall footprint for the same performance.



2.2.6 Canceling stray field without shield

In AC applications, external stray fields can be cancelled out by the microcontroller. Computing the difference between max and min sensor output values provides a signal independent of any parasitic DC field.



2.2.7 Avoiding cross-talk without shield

Even **without ferromagnetic shield**, cross-talk between adjacent current tracks can be avoided by design. Figure 6 illustrates a concept of current trace layout with slots to force the current to flow perpendicular to the main track axis. The sensors are rotated by 90° with their sensitive axis (blue arrow) parallel to the current trace. With such a configuration, there is virtually no cross-talk between phases.

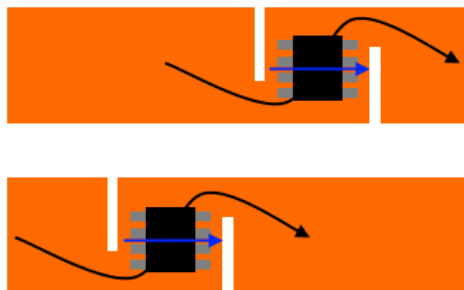
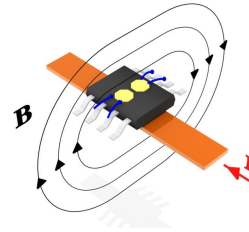


Figure 6: Current trace layout with slots and rotated sensors to avoid cross-talk between phases.

2.3 Quick Selection Guide



2.3.1 Main features

	91205	91206	91208
Sensitivity [mV/mT] (*programmable)			
▪ Very High Field version	-	-	30-200*
▪ High Field version	100	60-330*	50-300*
▪ Low Field version	280	200-700*	100-700*
Thermal sensitivity drift [%]	±2	±1.5	±1.5
Thermal offset drift [mV]	±50	±20	±10
Non-linearity [%F.S.]	±0.5	±0.5	±0.5
Response time [μs]	8	8	3
Bandwidth [kHz]	100	100	250
Analog output	Yes	Yes	Yes
PWM output	No	Yes	No
Programmable	No	Yes	Yes
Diagnostic functions			
▪ Over/Under-voltage detection	No	Yes	Yes
▪ Broken-track detection	No	Yes	No
▪ Clamping	No	Yes	No
Package	SOIC-8	SOIC-8	SOIC-8
Temp. range [°C]	-40-125	-40-150	-40-150

Table 4: Main features and specifications of planar IMC-Hall® current sensors.

2.3.2 Option code and sensitivity range

Sensor	Option code	IMC version	Sensitivity range [mV/mT]
MLX91205	AAL-003	LF	280
	AAH-003	HF	100
MLX91206	CAL-001	LF	460-700 (580)
	CAL-002	LF	300-470 (380)
	CAL-003	LF	200-310 (250)
	CAH-001	HF	210-330 (270)
	CAH-002	HF	130-220 (170)
	CAH-003	HF	80-140 (110)
	CAH-004	HF	60-110 (77.5)
	CAL-000	LF	100-700 (250)
MLX91208	CAH-000	HF	50-300 (100)
	CAV-000	VHF	30-200 (40)

Table 5: Option code and sensitivity range of planar IMC-Hall® current sensors.

2.4 PCB Design: Guideline

The PCB design and layout plays an important role in the final performances of the current sensing module. More specifically, two different aspects are to be considered when designing the ground layer on the PCB.

When an application implies high voltage switching (for instance in motor control applications), an expanded ground layer, as depicted Figure 7:, will help reducing the parasitic coupling capacitance generated by dV/dt transients.

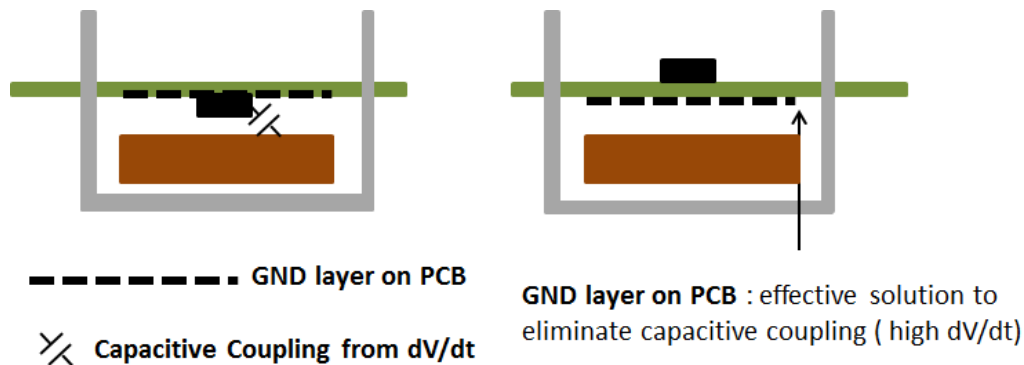


Figure 7: Current sensing structure – Expanded Ground Layer on PCB in order to reduce the parasitic coupling capacitance (coming from dV/dt transients).

At the same time, the ground layer can have a big impact on the response time.

If the ground layer covers all the surface of the PCB and surrounds the two legs of the shield, Eddy currents will start to flow circularly around the legs of the shield, generating a counter-magnetic field which slows down the response time of the sensor.

In order to avoid increased response time, the ground layer should be divided such that it interrupts the circulations of Eddy currents around the shield.

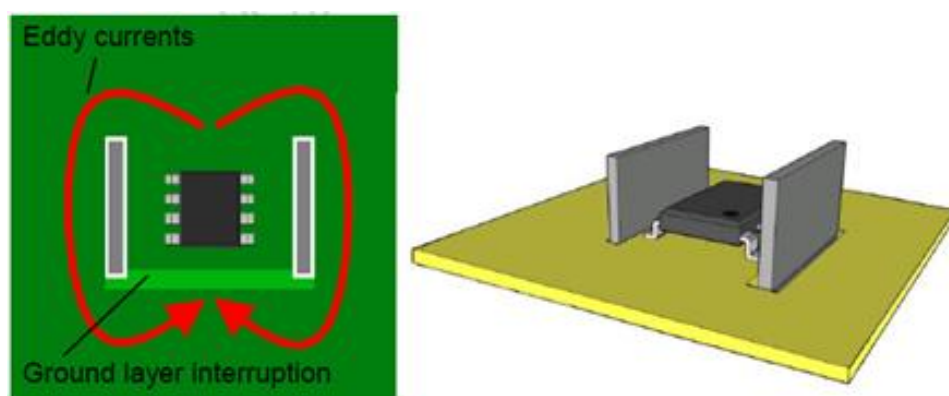


Figure 8: Current Sensing Structure – Designing the Ground Layer on the PCB such that Eddy Currents circulations is interrupted

2.5 Reference Designs

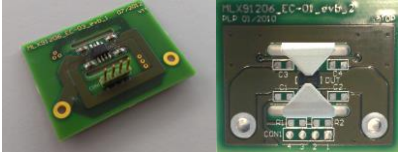
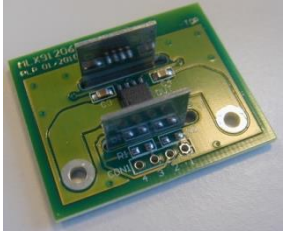
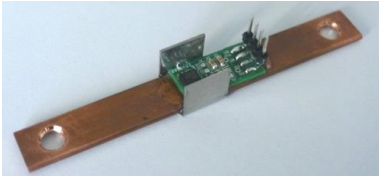
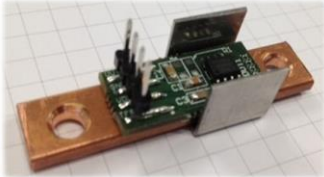
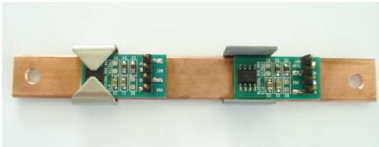
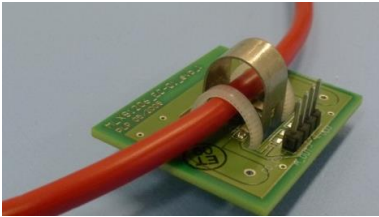
Application	Solution	Illustration
PCB trace current 2-10A	Multi-turn and multi-layer PCB Single layer PCB with C-shaped ferromagnetic shield	
PCB trace current 10-50A	Single layer PCB with or without ferromagnetic shield	
Bus bar 50-250A	High field sensor with 12mm U-shaped ferromagnetic shield	
Bus bar 300-700A	Very high field sensor with 12mm U-shaped ferromagnetic shield	
High dynamic range 50mA to 250A	Dual range sensor with U-shaped and C-shaped shields	
Non-intrusive current sensing from cable 10-100A	Simple PCB with clamp-on shield wrapped around the cable	

Table 6: Overview of the reference designs based on planar IMC-Hall® current sensors.

2.5.1 PCB application, 2-10A range, multi-layer/multi-turn solution

- PCB with multiple layers and trace windings (current loops) for very high sensitivity.
- Can be used with or without ferromagnetic shield, depending on sensitivity and accuracy requirements.

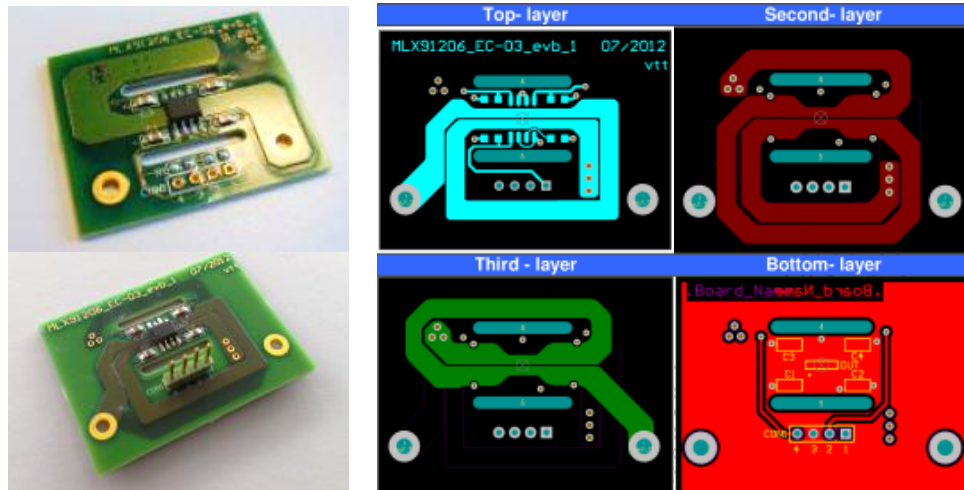


Figure 9: PCB layout example for very high sensitivity with 6 windings on 3 layers.

	3 windings w/o shield	3 windings w/ shield	6 windings w/o shield	6 windings w/ shield
Sensitivity (max) [mV/A]	210	350	420	700

Figure 10: Maximum achievable sensitivities with Melexis evaluation boards.

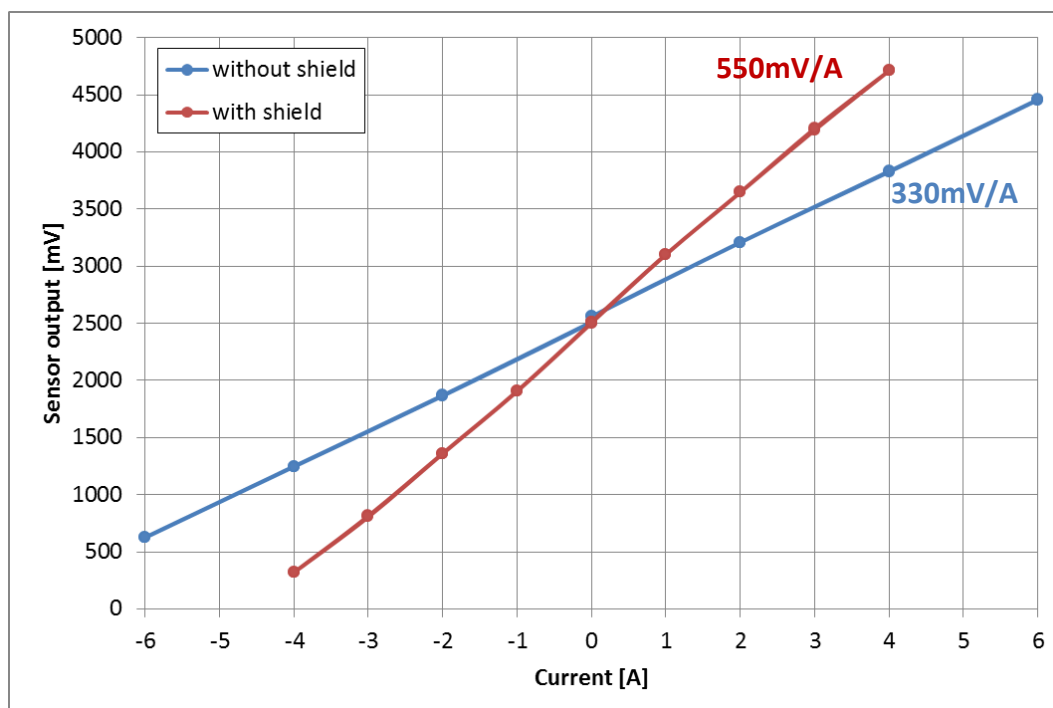
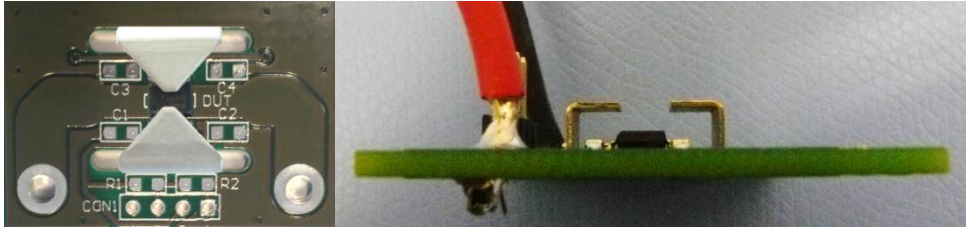


Figure 11: Example of output functions for a six-winding evaluation board, with/without shield.

2.5.2 PCB application, 2-10A range, ferromagnetic shield solution

- PCB with one layer and a single current trace (no windings).
- Closed ferromagnetic shield for high magnetic gain.



Assembly Concepts

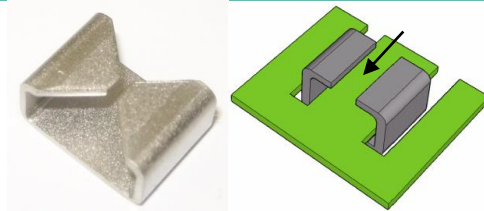


Figure 12: Shield in one piece inserted through slots on the PCB edge.

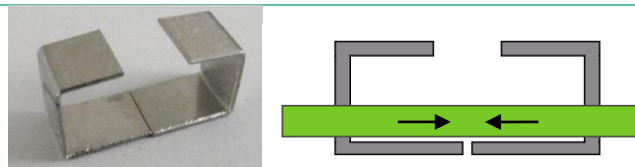


Figure 13: Shield in two parts inserted in PCB slits and assembled together.

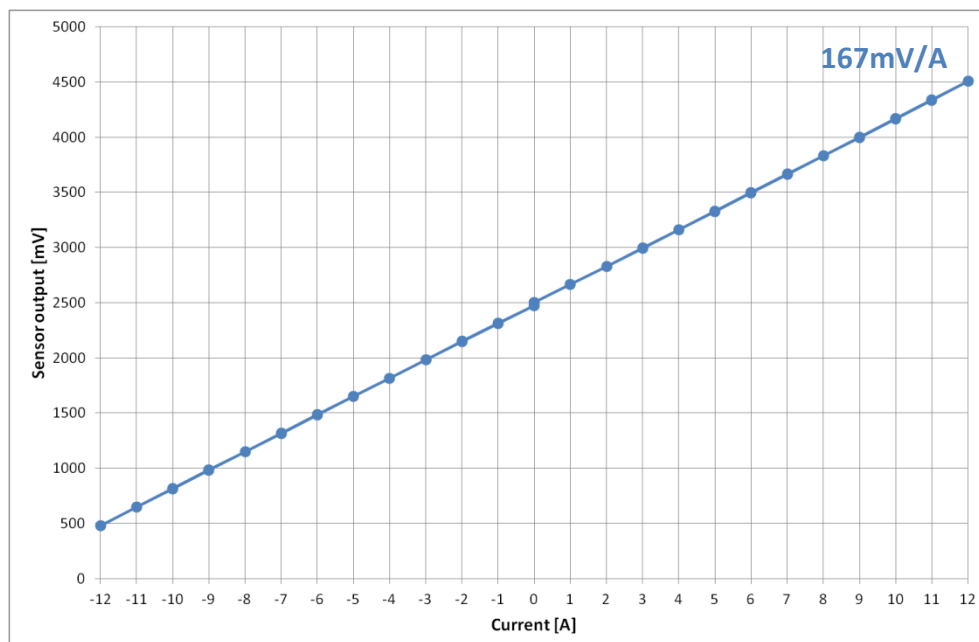


Figure 14: Example of output function for a single-layer PCB with closed shield.

2.5.3 PCB application, 10-50A range

- PCB with one layer and a single current trace.
- To be used with or without ferromagnetic shield (U-shaped).
- **Sensitivity:** up to 60mV/A (without shield) and 170mV/A (with shield).

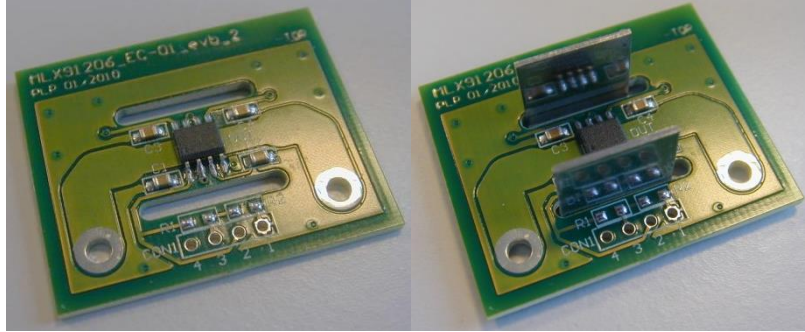


Figure 15: Single-layer evaluation board without and with shield.

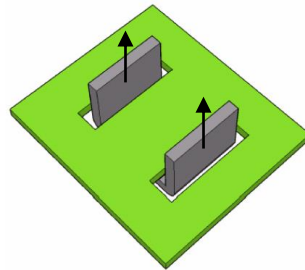


Figure 16: Shield assembly through PCB slits.

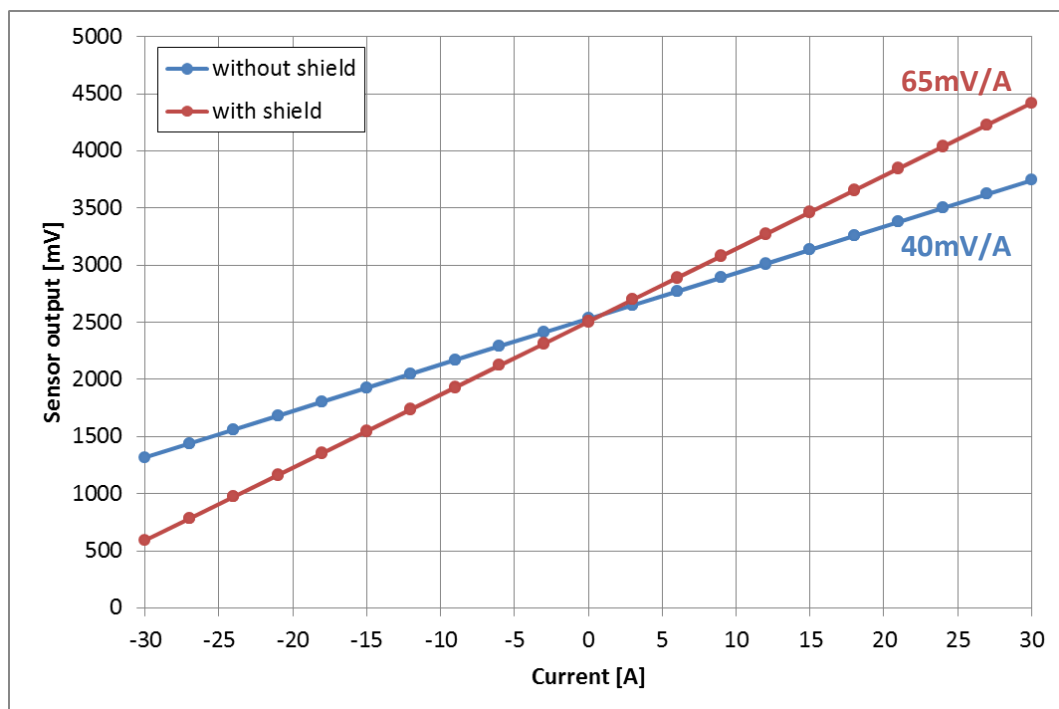


Figure 17: Example of output function for a single-layer PCB, with/without shield.

2.5.4 Bus bar application, 50-250A range

- The high field (HF) sensor on PCB is mounted directly above the conductor.
- A simple, low-cost and compact U-shaped shield is mounted around the sensor to protect it from stray fields and ensure good signal robustness against vibrations and displacements.
- With the dimensions demonstrated here, the linearity error is lower than $\pm 1.5\text{A}$ up to $\pm 250\text{A}$.

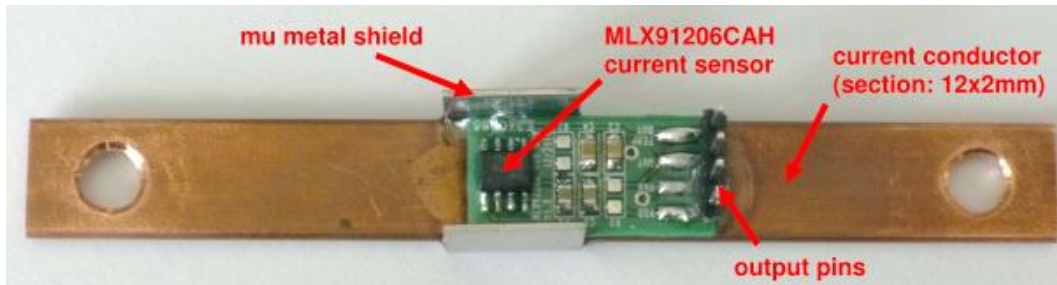


Figure 18: Demonstrator based on MLX91206 HF sensor and U12 shield with 0.8mm thickness.

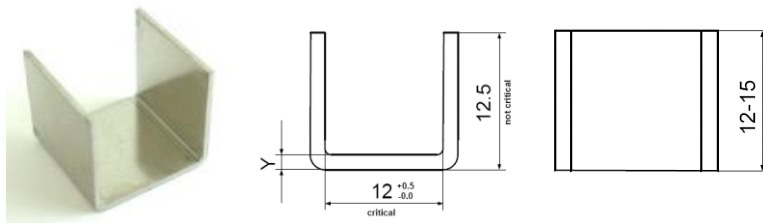


Figure 19: Shield dimensions.

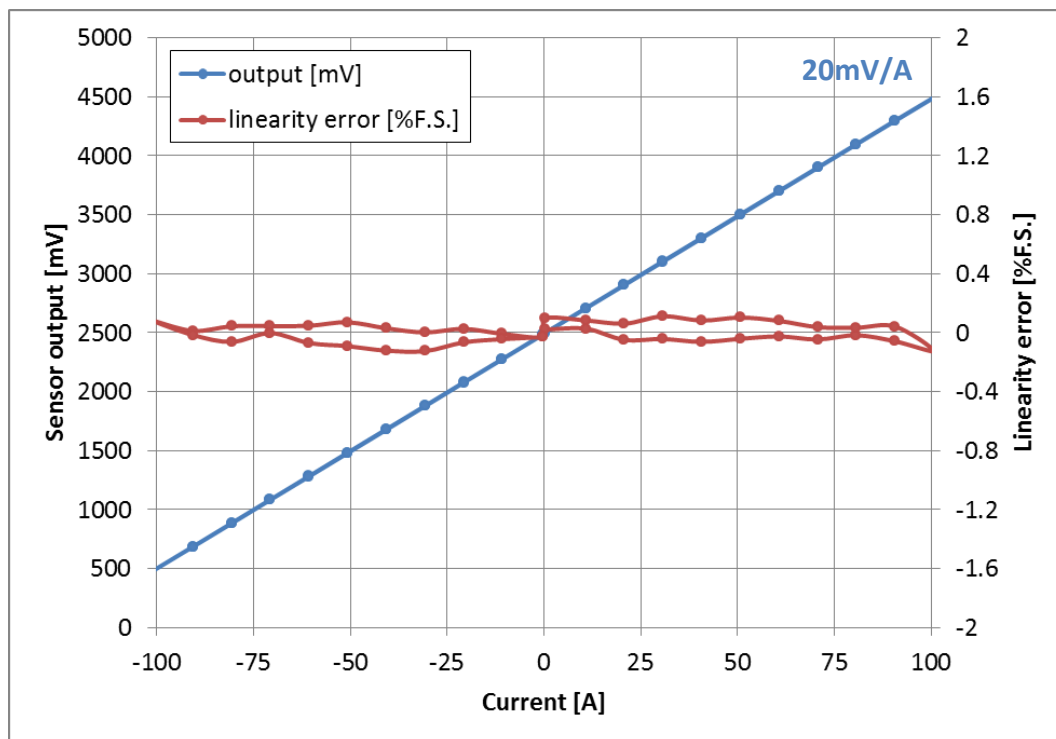


Figure 20: Typical output and non-linearity of a sensor calibrated for $\pm 100\text{A}$.

2.5.5 Bus bar application, 300-700A range

- With the very high field (VHF) sensor, the measurement range can be extended to 700A while keeping the same inner width than for the previous design (12mm). Only the shield thickness must be adapted from 0.8 to 1.5mm.
- The linearity error is lower than $\pm 5A$ up to $\pm 650A$.
- Very compact solution to measure 700A with a footprint of less than $2cm^2$.

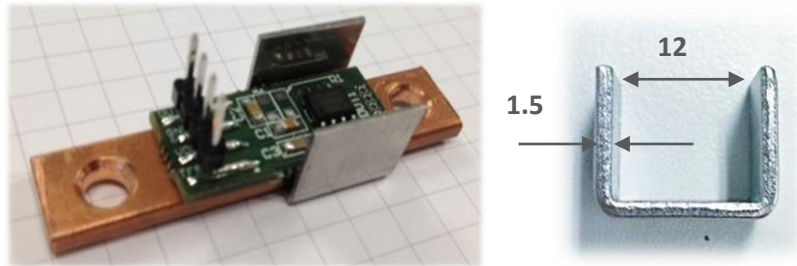


Figure 21: Demonstrator based on MLX91208 VHF sensor and U12 shield with 1.5mm thickness.

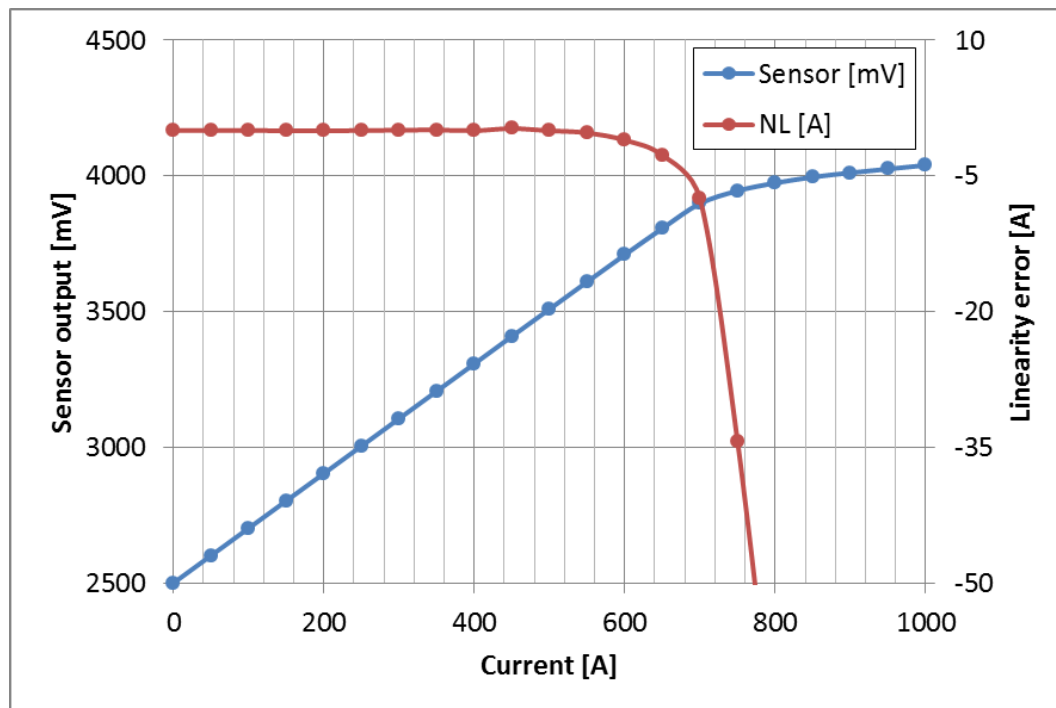
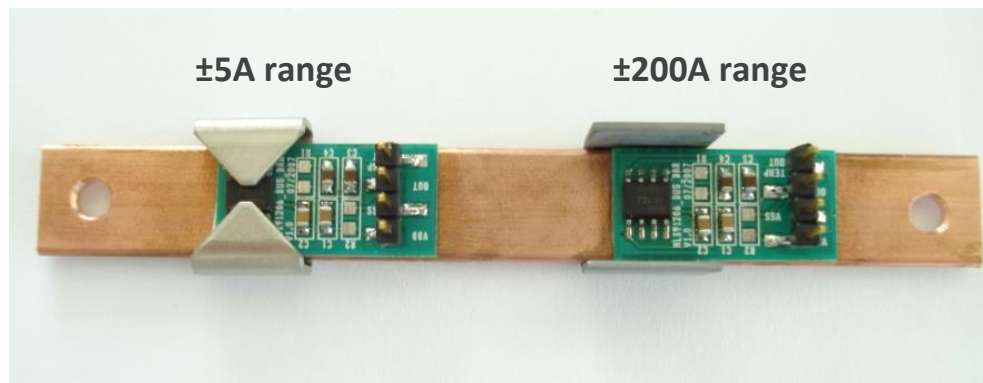
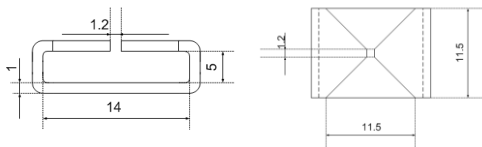
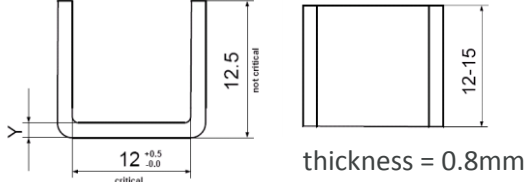


Figure 22: Sensor output and linearity error versus current.

2.5.6 Bus bar application, dual range 5A/200A

- Solution for applications with a wide dynamic range.
- One sensor with C-shaped (closed) shield for high accuracy at small currents (typ. $\pm 5\text{A}$).
- One sensor with U-shaped shield for high saturation limit (typ. $\pm 200\text{A}$).
- Other combinations of ranges are possible depending on the application requirements.



View	Dimension [mm]
	
	

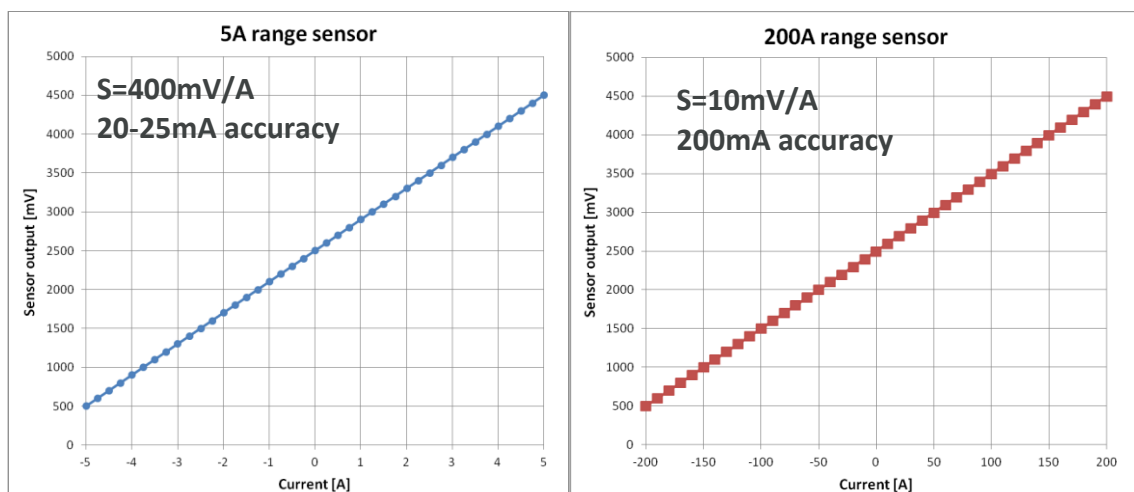


Figure 23: Typical output of the 5A and 200A range sensors.

2.5.7 Cable application, 10-100A range

- The clamp-on shield gathers the magnetic field around the cable and concentrates it above the sensor package. Small air gap ensures high magnetic gain.
- Shield geometry can be adapted to match various cable diameters and current ranges.

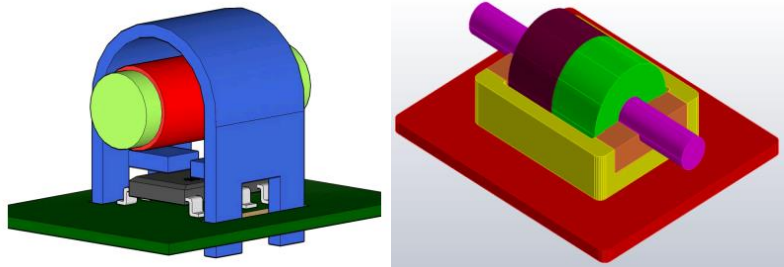


Figure 24: Cable clamp concepts (left: monolithic shield, right: two-part shield in plastic housing).

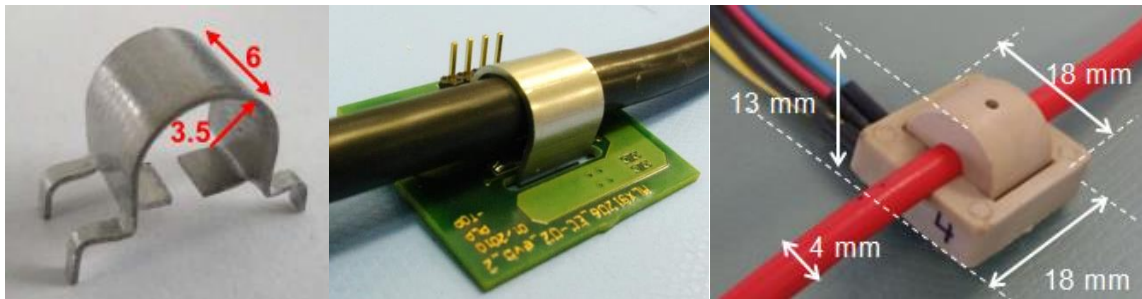


Figure 25: Implementation examples (monolithic and two-part shield in plastic housing).

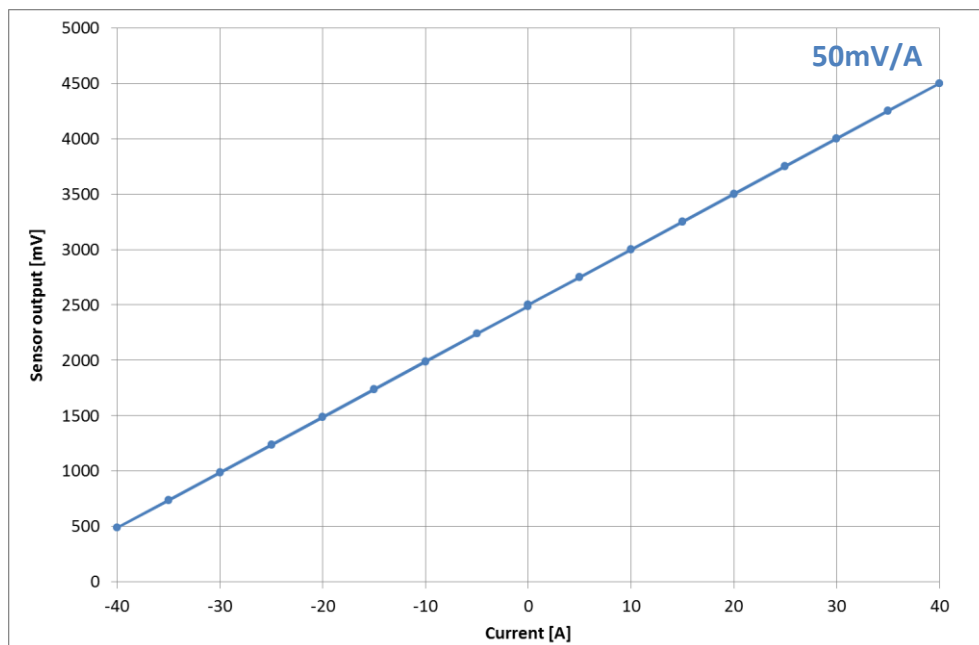


Figure 26: Example of output function with a cable-clamp demonstrator calibrated for $\pm 40\text{A}$.

Ferromagnetic materials

3.1 Suppliers

Melexis partnered with magLab and PML India for ferromagnetic material supply.



www.maglab.ch

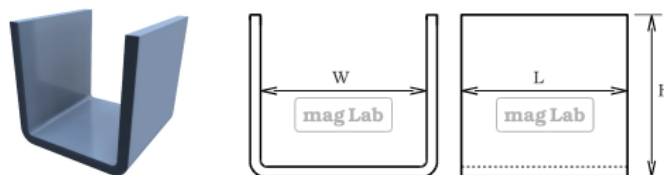


www.pmlindia.com

Recently, PML and magLab signed an exclusive collaboration in the field of contactless current sensing. This cooperation between magLab and PML offers an efficient and cost-effective solution for customers requiring magnetic shields. magLab takes care of the engineering side, while PML manufactures the products to our specifications.

3.2 Ferromagnetic shields

3.2.1 Standard U-Shield



Order Codes: U-Shield – Width – Length – Height – Thickness (– Ni)

U-Shield (order code example)	-[W]-	-[L]-	-[H]-	-[T]
U-Shield-12-13-12.5-0.8 (standard)	W=12	L=13	H=12.5	T=0.8

(all dimensions: mm)

Material Specification	U-Shield-W-L-H-[T]	-[Ni] ⁻¹ (%)
Standard thickness: 0.8mm / 48% Ni	T=0.8	Ni=48
Other thickness options 0.35/0.5/1/1.2 mm (on request)	T=...	Ni=...

Figure 27: Ordering information for the standard U-shield from MagLab.

3.2.2 Mechanical assembly

Ferromagnetic shields can be assembled by crimping, screwing or bonding (glue or tape). They can also be encapsulated in a pre-molded plastic case. The optimal solution depends on the application. In any case, care should be taken to avoid mechanical stress on the part of the shield involved in the magnetic measuring circuit.

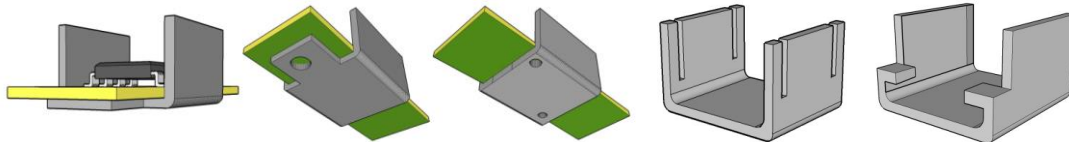


Figure 28: Several solutions for shield assembly.

One of the most common solutions is to use a pre-molded plastic case, with slots to insert the shields, as illustrated on the pictures below.

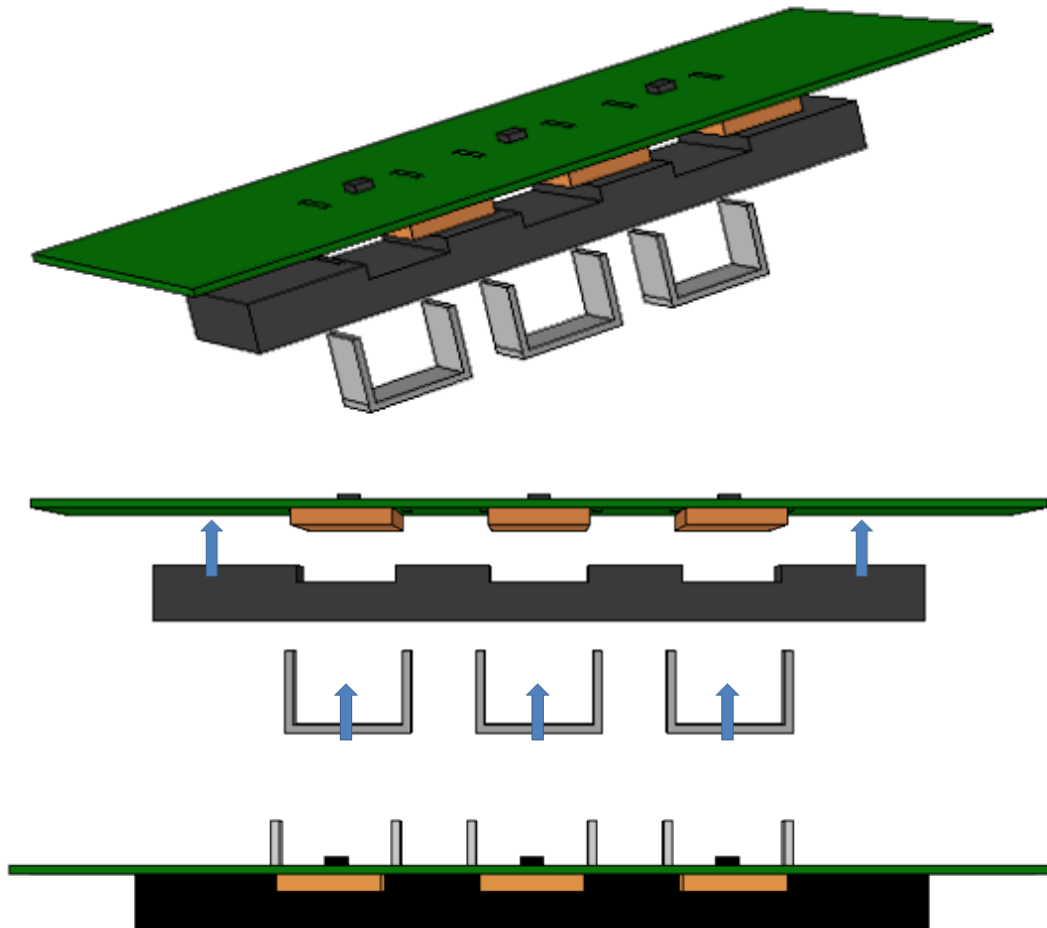


Figure 29: Assembly with pre-molded plastic case.

3.3 Ferromagnetic cores

The performance of the current sensing solution relies on the careful selection of a proper core geometry, material and manufacturing conditions (annealing, lamination, etc.). Table 7 displays the main features of the most common material types.

Material type	Saturation	Speed	Price	
Ferrite	0.5T	Fast	\$	
Silicon Iron (SiFe)	1.6T	Medium	\$\$	
Nickel Iron (NiFe)	1.4T	Fast	\$\$\$	

Table 7: Features of most common ferromagnetic core materials.

Figure 30 shows the linearity and hysteresis of 3 geometrically identical cores made of the most common ferromagnetic materials, for comparison purposes.

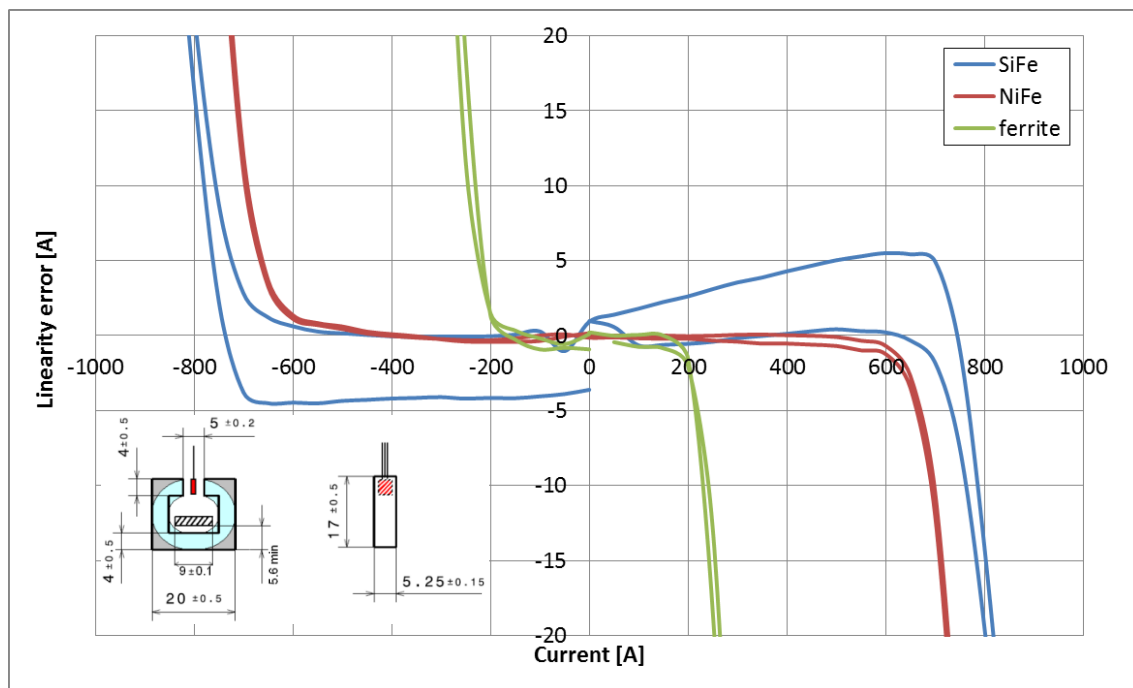


Figure 30: Linearity error and hysteresis of the most common ferromagnetic core materials.

End-of-line Calibration

3.4 Introduction

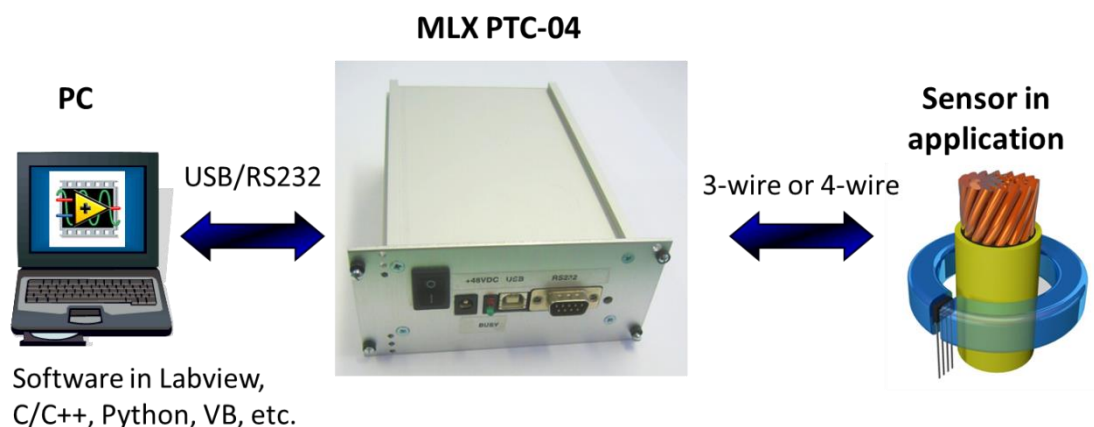
Each current sensor is individually tested and calibrated over temperature on the Melexis production line. However, in order to achieve optimal accuracy, a final calibration is required at customer-side after assembly to compensate for mechanical tolerances (sensor position deviations, shield dimensions, etc.)

This final calibration can be done in two ways: either by using the Melexis tools to directly program the sensor EEPROM, or by adjusting the gain/offset at microcontroller level.

3.5 Direct sensor calibration

All recent current sensor products (starting from MLX91206) can be programmed using the Melexis universal programmer (PTC-04) and related software. The PTC-04 communicates with the sensor through 3- or 4-wire connectors, and with the PC through USB or RS-232. Melexis provides a library of sensor-specific high level functions (.dll), which can be used to develop custom software using common programming language (C/C++, Labview, etc.)

The calibration is a fast two-step process: the sensor output function (gain and offset) is adjusted automatically based on two reference measurements (i.e. zero current and nominal current).



3.6 Micro-controller level calibration

A micro-controller level correction is recommended for multi-sensors applications, i.e. on power distribution units, where typically 12 to 24 sensors are on the same PCB in order to monitor the current of each channel.

All Melexis current sensors are factory calibrated over temperature. After assembling of the factory-calibrated sensors on each channel, a reference current is applied on each channel. The output voltage of each sensor is measured and the required corrective factor is thus calculated and stored in the microcontroller.

Additional Information

Please refer to the following documents for additional information on specific topics:

Design guide for low currents

<http://melexis.com/Assets/Small-Currents-Design-Guide-6252.aspx>

Design guide for high currents

<http://melexis.com/Assets/High-Currents-Design-Guide-6253.aspx>

Power distribution units (PDU) applications

[http://melexis.com/Assets/Current-Sensors-Deployment-in-PDU-\(Power-Distribution-Unit\)-Applications-6092.aspx](http://melexis.com/Assets/Current-Sensors-Deployment-in-PDU-(Power-Distribution-Unit)-Applications-6092.aspx)

Magnetic linearity and hysteresis

Application note focusing on the magnetic performance of Hall sensors and ferromagnetic materials.

<http://melexis.com/Assets/Magnetic-linearity-and-hysteresis-6477.aspx>

Contact Us

Please contact our current sensor team for more information.

Amalia Spataru (apa@melexis.com)

Simon Houis (shu@melexis.com)

Robert Racz (ror@melexis.com)