TÉCNICO LISBOA

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Microsistemas e Nanotecnologias

1st Cycle Integrated Project in Engineering Physics (PIC 1)

Advanced sensors for current monitoring in the next generation of power devices

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Summary

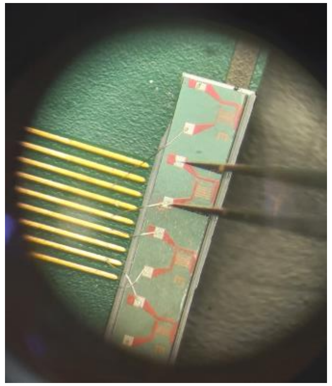
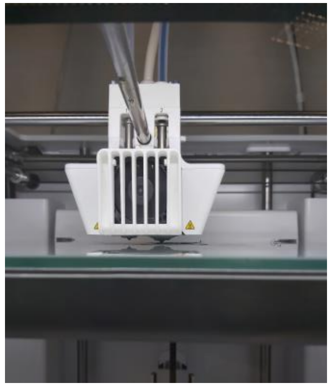
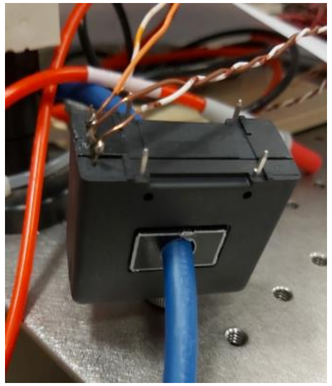
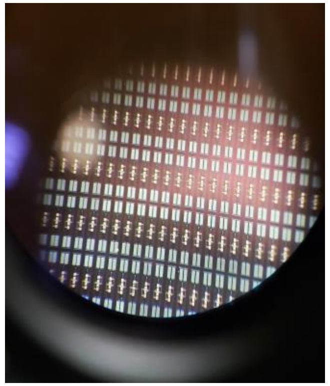
Current sensors - detect the operating current of a device in real time;

- used for **power monitoring systems** and **energy meters**;

- techniques with different operating principles; by direct connection or **indirectly**.

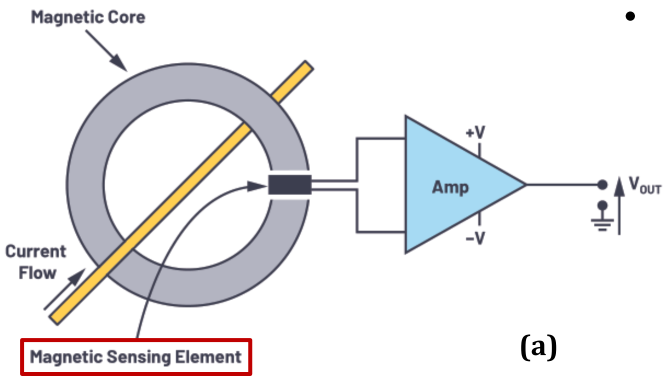
▶ **This work aims to study magnetoresistive sensors, a viable solution for the next generation of batteries.**

- Current sensing techniques
- Magnetoresistive sensors
- Characterization of samples (TMR and GMR)
- Characterization of commercial current sensor
- Designing 3D model for measurements in a fixed position
- Developing a new measurement interface

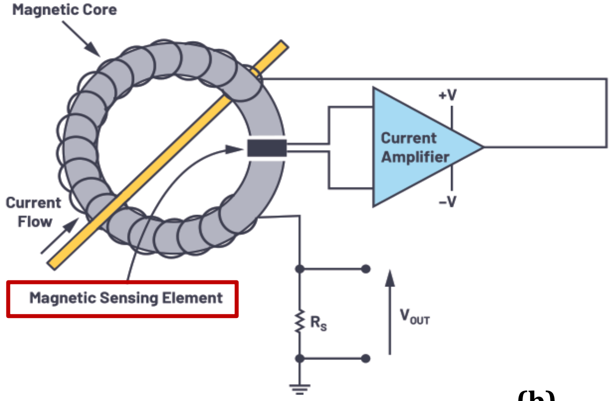





Current sensing techniques

► Open-loop and closed-loop



(a)



(b)

- Open-loop **(a)** and closed-loop **(b)** technologies in current transducers

- **High μ** ring concentrates H lines onto the sensor:
  - amplification limits bandwidth;
  - skin effect limits accuracy;
  - hysteresis and eddy currents;
  - overcurrent can saturate magnetic core.

- **Closed-loop:** i_S through second transformer winding**:**
  - improves linearity and accuracy;
  - practically no eddy currents or hysteresis losses;
  - requires higher current supply and additional circuitry (limits bandwidth).

► Magnetoresistive (MR) sensors

- **Linear magnetic field transducers** based on:
  - → intrinsic magnetoresistance of ferromagnetic material (**AMR**);
  - → ferromagnetic/non-magnetic heterostructures (**GMR** and **TMR**).

- ► Resistance varies due to external magnetic field → $\boldsymbol{R(H)}$;
- ► able to detect weaker magnetic fields → gradually replaced Hall sensors in hard drives and current sensing applications;
- ► easily **scalable** with micro and nanofabrication techniques (allows for very small devices);
- ► hysteresis effects often negligible.

- **Hysteresis**, **linear range** and **sensitivity** are examples of parameters set differently for different products.

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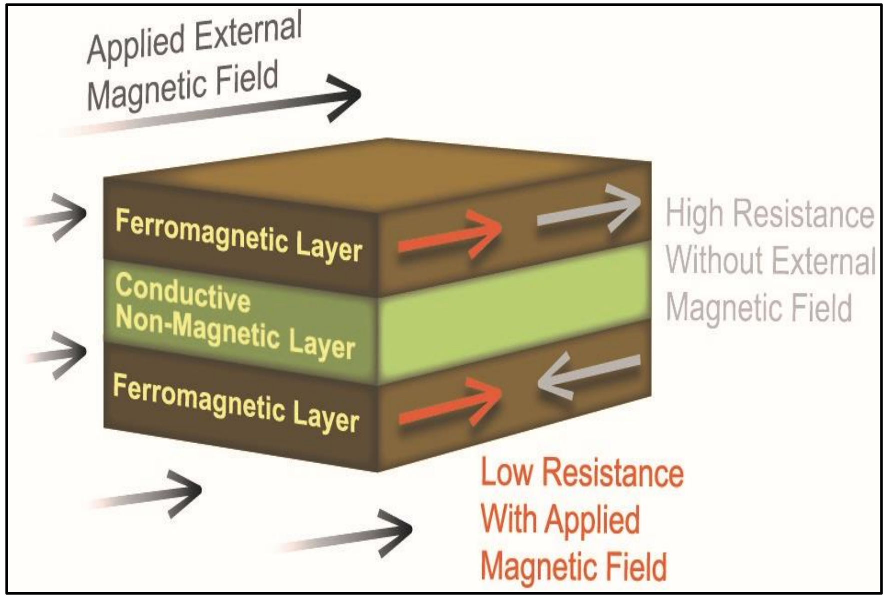
Magnetoresistive sensors

Anisotropic Magnetoresistance (AMR)

- **Current** I in **ferromagnetic material** experiences R dependent on angle with **magnetization** M, changed because of H_{ext};
- R_{min} when I **parallel** to M, R_{max} when I **perpendicular** to M;
- high thermal drift and non-linearity; higher sensitivities than Hall sensors, but lower than GMR and TMR.

Giant Magnetoresistance (GMR)

- Non-magnetic conductive layer (such as copper layer) between two FM layers – **free layer** (M changes direction) and **pinned layer** (fixed orientation):
  - middle layer thinner than mean free path of electrons (a few nm).
- **spin-dependent electron scattering**:
  - magnetizations in the <u>same direction</u> → only one type of electron scattered significantly;
  - magnetizations in <u>opposite directions</u> → more electrons experience scattering → increase in R.
- higher ΔR, thus weaker H can be measured, currents below the detection limit of AMR or Hall effect sensors are detected.



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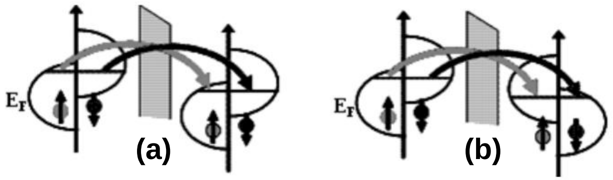
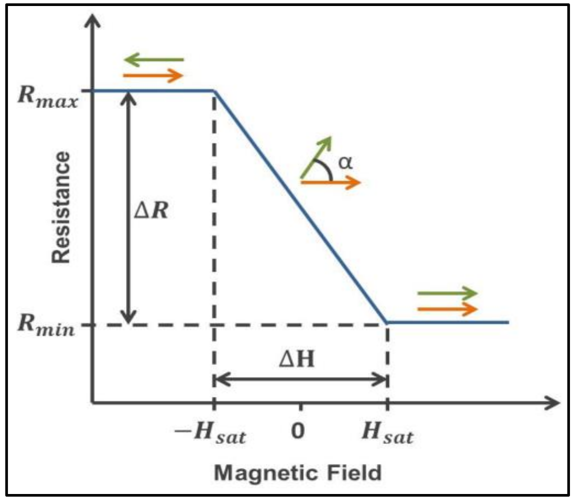
Magnetoresistive sensors

Tunnel Magnetoresistance (TMR)

- Similar to GMR, but uses an **insulator** (instead of a conductor) - typically of aluminum oxide (Al_2O_3) or magnesium oxide (MgO);
- relative orientation of M in the FM layers determined by **spin-dependent tunneling** of electrons across the insulator;
- **anti-parallel state** → tunneling between spin bands with higher and spin bands with lower DOS, leading to lower conductance; **parallel state** → tunneling between spin bands with similar DOS. R inversely proportional to the conductance, thus $\boldsymbol{R_{\uparrow\downarrow}} > \boldsymbol{R_{\uparrow\uparrow}}$.



➢ Schematic band structure for electrons tunnelling in the parallel state **(a)** and anti-parallel state **(b)**



➢ Ideal **transfer curve** and magnetization directions in the FM layers (the parallel configuration was defined here for $H > 0$)

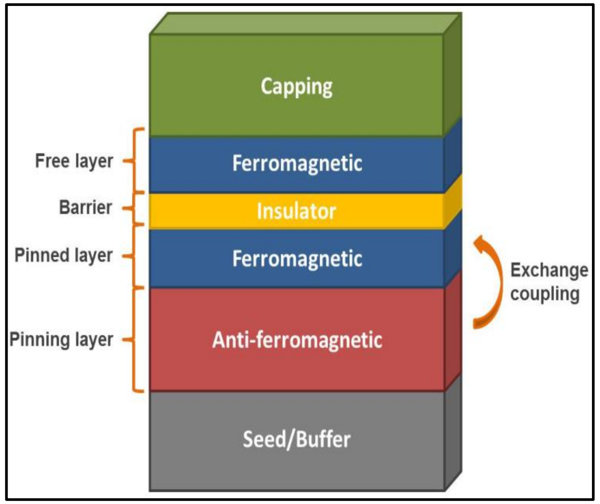
- **Magnetoresistance level:**

$$\boxed{\boldsymbol{MR}(\%) = \frac{R_{max} - R_{min}}{R_{min}}}$$

- **Sensor field sensitivity:**

$$\boxed{\boldsymbol{S} = \frac{1}{R_{min}}\left(\frac{\Delta R}{\Delta H}\right)_{\text{linear}} = \frac{MR(\%)}{(\Delta H)_{\text{linear}}} \quad [\%/\text{Oe}]}$$

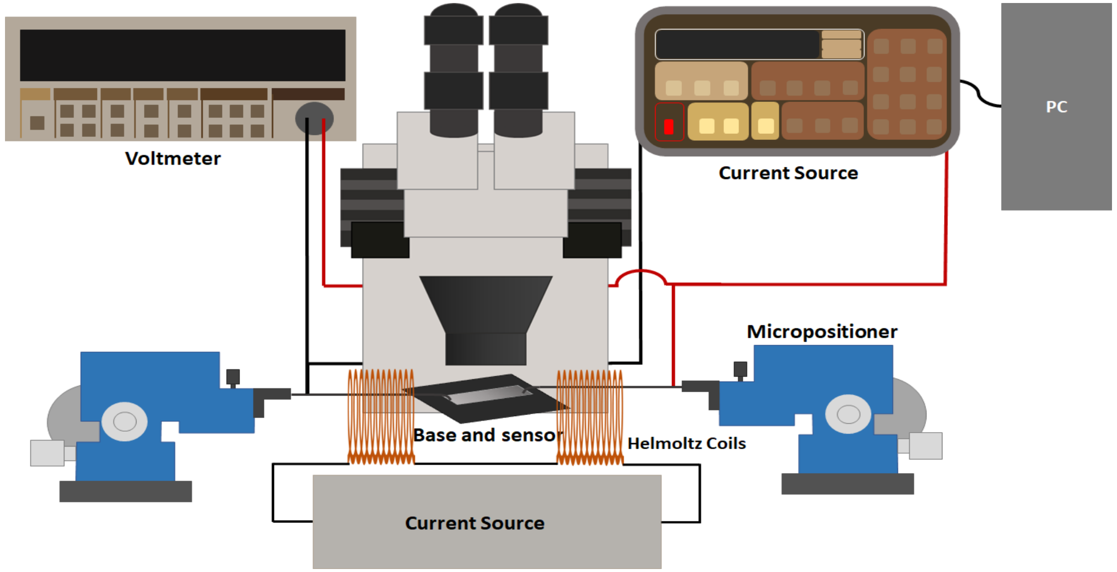
$$(R_{max} \equiv R_{\uparrow\downarrow}\,,\ \ R_{min} \equiv R_{\uparrow\uparrow})$$

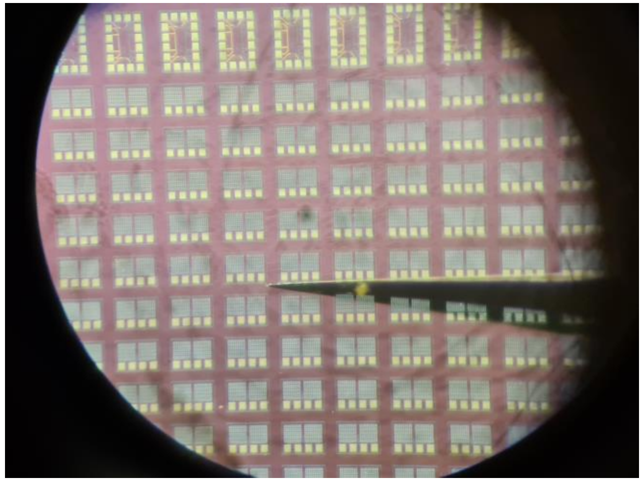


➢ Basic structure of a MTJ sensor, in which electrons can cross the thin isolating layer by means of **quantum tunneling**

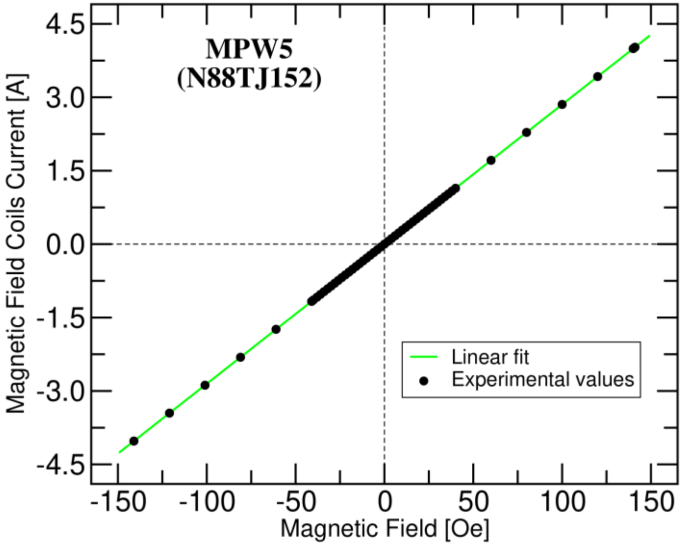
Characterization of samples (TMR and GMR)

Characterization setup





Minimum sample size!



- Range $[-\mathbf{141}, \mathbf{141}]\mathbf{Oe}$ for the magnetic field H (with reverse magnetic field sweep), generated by current in the coils;
- bias current of $\boldsymbol{I_{bias}} = \mathbf{1}\boldsymbol{\mu A}$ $(V = R \cdot I_{bias})$;
- constant of proportionality $k = (35.05 \pm 0.03)\mathrm{Oe/A}$ between H and I;
- needles of the **micropositioners** put over the samples.

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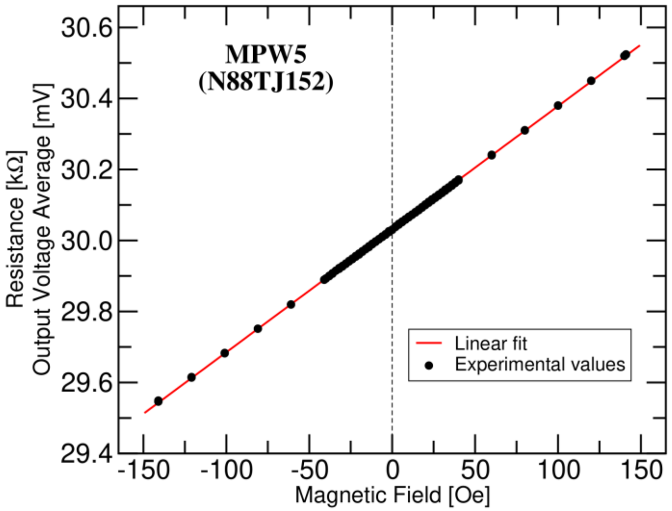
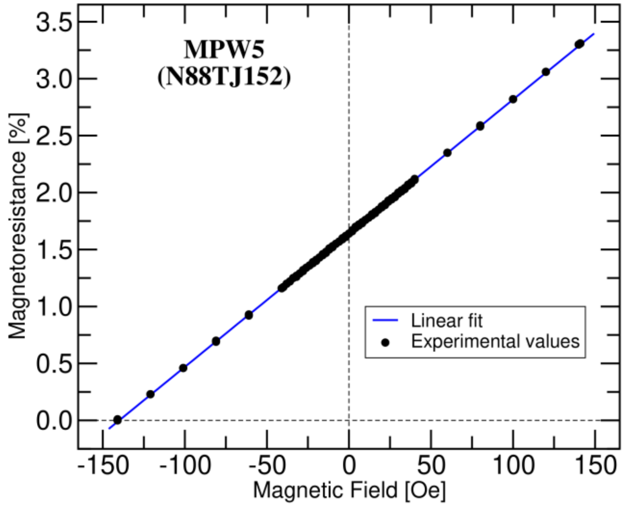
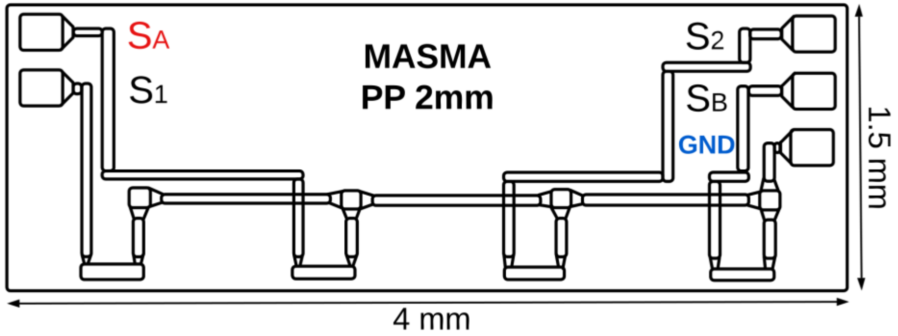
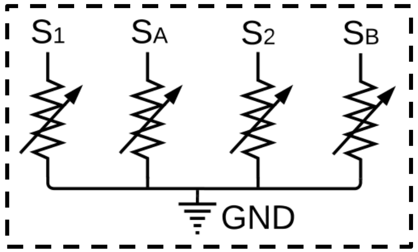
Characterization of the first sample

MPW5 (N88TJ152) – TMR technology







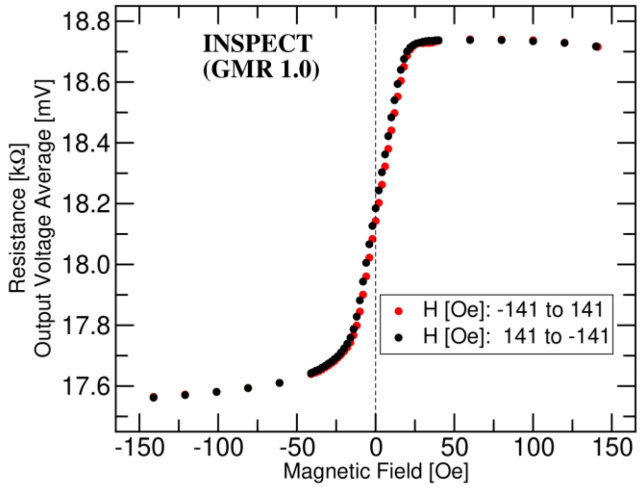


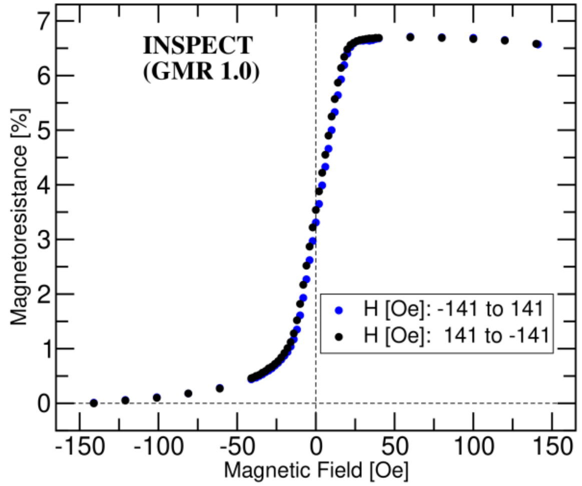
- Sample with four sensors (S_A, S_B, S_1 and S_2) with analogous characteristics; needles placed over S_A and GND;
- **selection of the bias current** → both noise and output signal proportional to it;
- the sensor has a **linear output** and **saturation is not reached**;
- $R(H)$ and $V(H)$ curves with **linearity error** of less than $\pm 0.21\%$;
- **no hysteresis** is apparent.

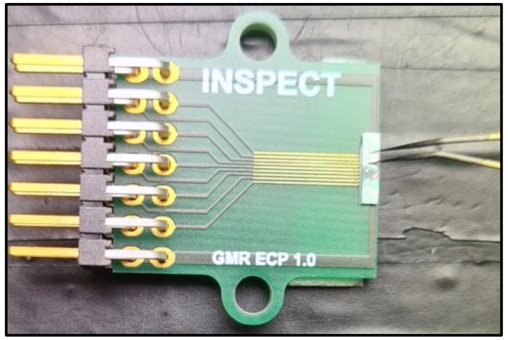
R_0 [kΩ]	R_{min} [kΩ]	R_{max} [kΩ]	$MR(\%)$*
30.02948	29.54624	30.52436	3.31

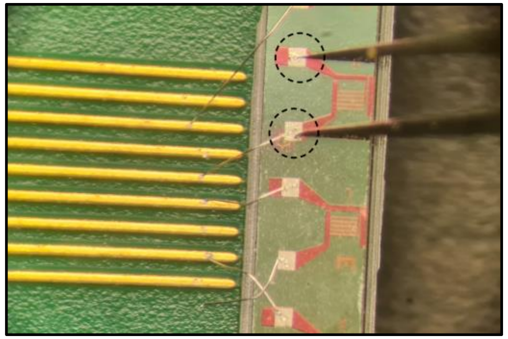
Characterization of the second sample

INSPECT (GMR ECP 1.0) – GMR technology









- Better sample to measure **smaller current values** (saturation is reached in the same H range);
- if two small currents are to be measured, output voltage difference will be more significant (**higher precision**);
- at too small current values: more significant impact of noise;
- minimum value of the resistance occurs far from the edge of the linear range;
- some **hysteresis** is noticeable → not favorable for practical applications, since the signal depends on the past conditions of the sensor.

R^*_{min} [kΩ]	R_{max} [kΩ]	$MR(\%)^*$	R_{min} [kΩ]	$MR(\%)$	$(\Delta H)_{\text{linear}}$ [Oe]	S [%/Oe]
17.56224	18.74039	6.71	17.61074	**6.41**	120	0.053

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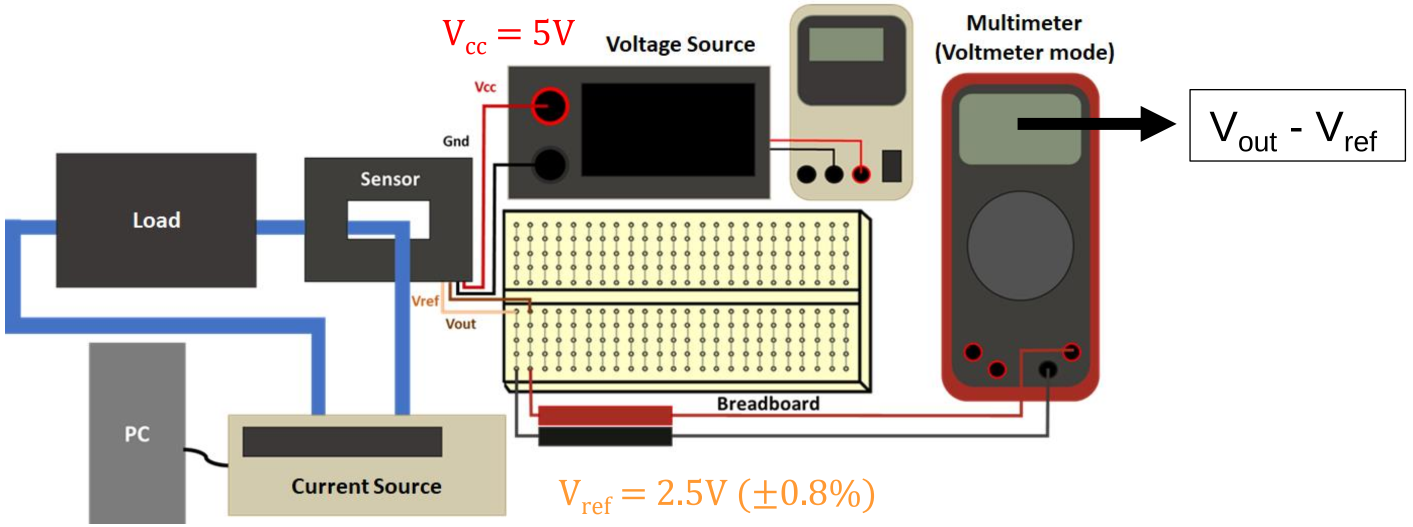
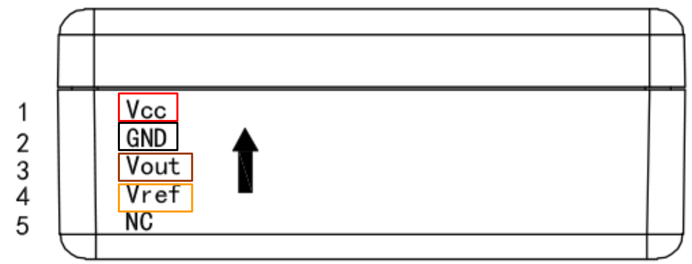
Characterization of STB-200LA/ZN current sensor

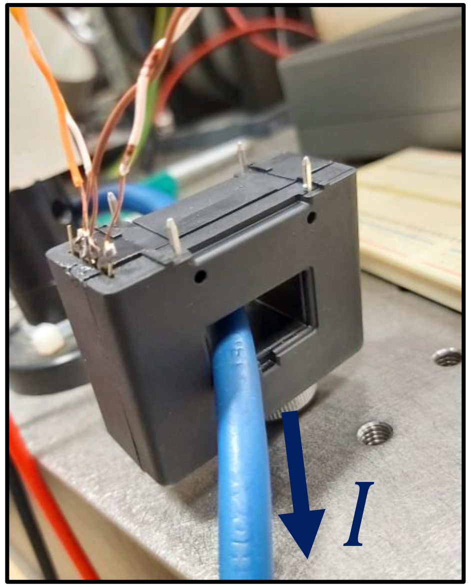




➢ Experimental setup in the Characterization Room

$$\boxed{H \approx \frac{I}{2\pi r}}$$

depends on distance r !

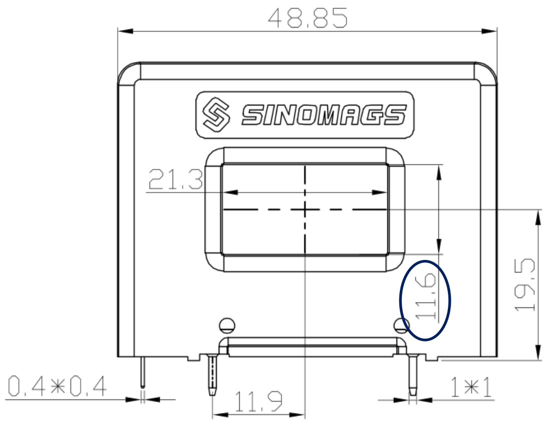


- **Current** generated in the current source flows through the wire:
  - generates **magnetic field H** which changes the resistance.

- magnetic sensor **STB-200LA/ZN** (produced by Sinomags™) based on a **closed-loop principle with TMR technology:**
  - can detect **DC**, AC, pulse and irregular signals.

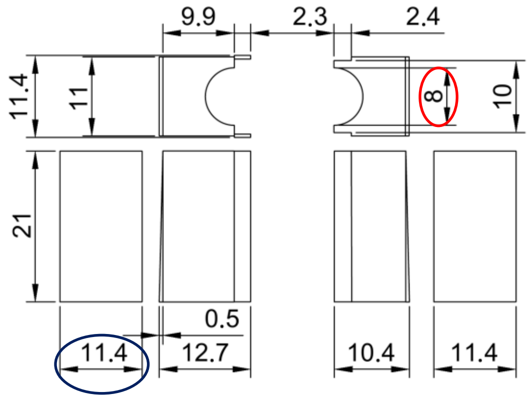
3D model for measurements with fixed distance

- **Dimensions of STB-xxxLA/ZN current sensors [±0.5mm]**

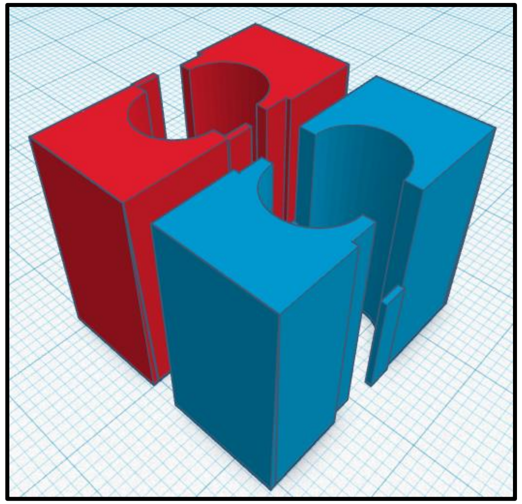


- Two pieces which mechanically fix together;
- small margins must be removed from the dimensions in the datasheet;
- 3D printed using a **PLA** (polyactic acid) based material.

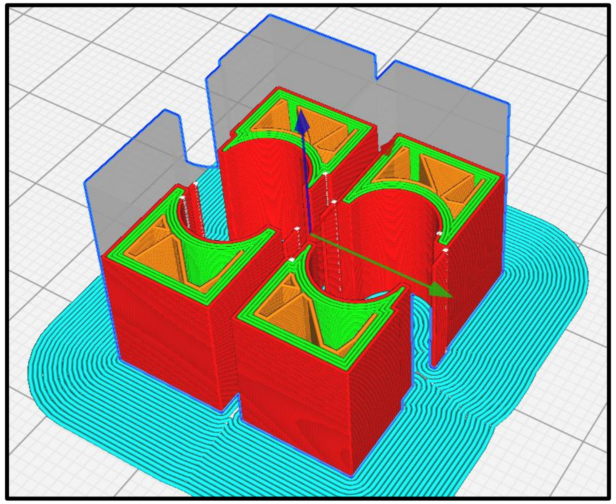
- **Dimensions of the 3D model [mm]**



- Wire diameter $d = (7.50 \pm 0.05)mm$

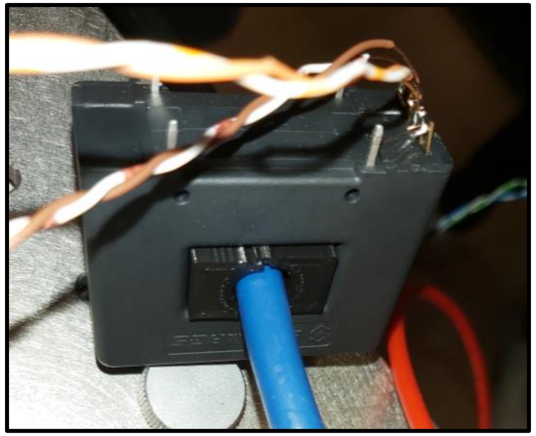


Autodesk Tinkercad



Ultimaker Cura

Ultimaker S3 → (3D printer)



- Measurements now obtainable in the **center** of the device.

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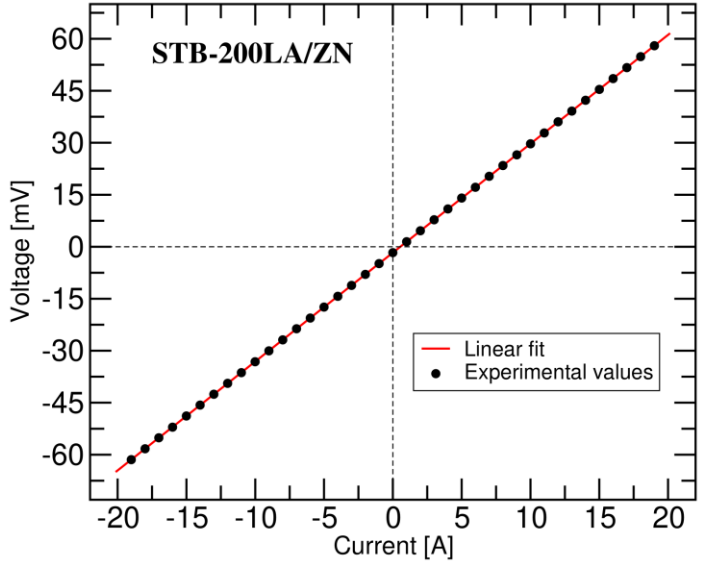
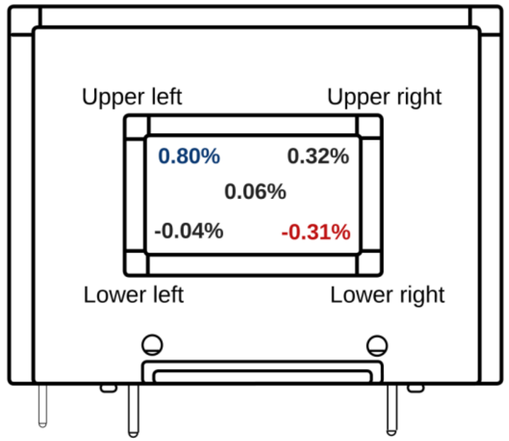
Characterization of STB-200LA/ZN current sensor



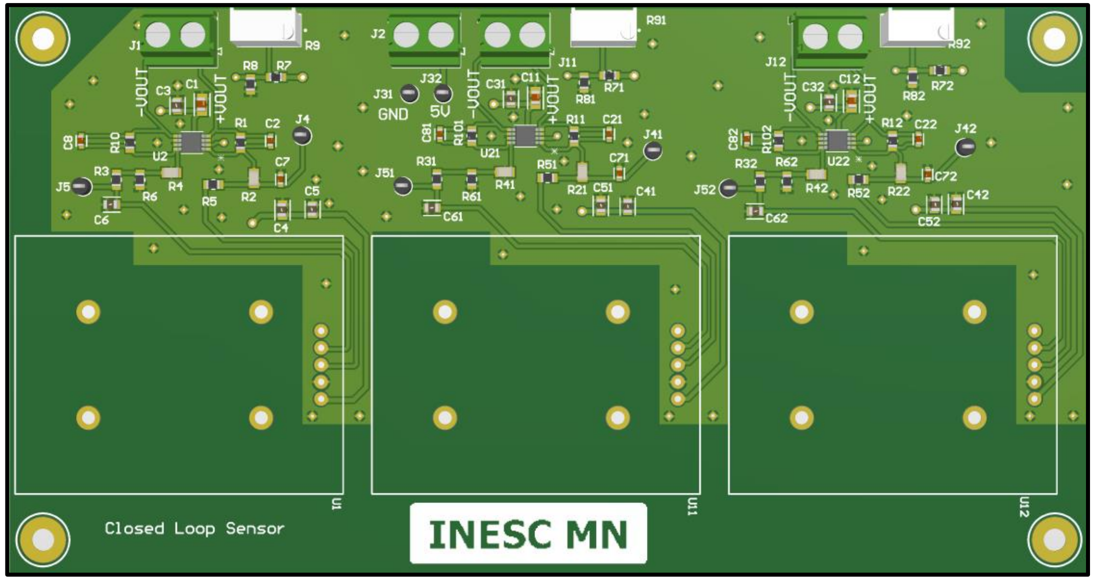


Linear fit V = k · I + b:

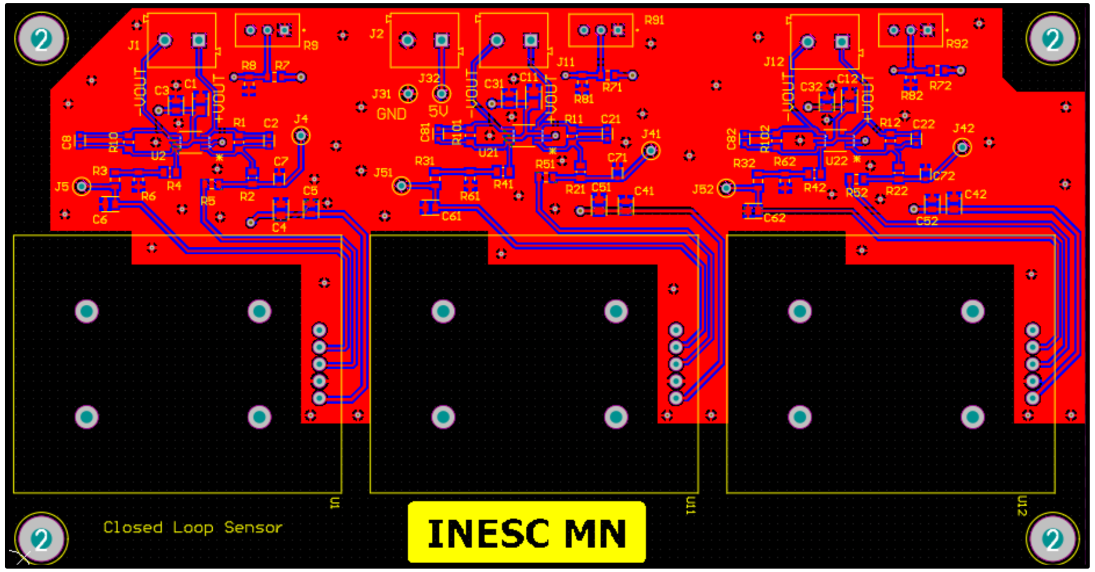
- <u>Slope:</u> $k = (3.142 \pm 0.003)$mV/A
  - differs **0.5%** from sensitivity 3.125mV/A in the datasheet.
- <u>Offset:</u> $b = (-1.70 \pm 0.02)$mV
  - **electrical offset voltage** of 5mV [($V_{out} - V_{ref}$) at I=0A] in the datasheet;
  - **oscillations** in current values;
  - **residual current** flowing in the wire;
  - other magnetic fields in the setup;
  - thermal drift (datasheet information for T=25ºC).
- Maximum **linearity error** of 0.87%, fitting parameter $\chi^2/n_d=0.05<1$.
- Average relative diferences to the average output voltage values at diferent positions:
  - dependence of the **magnetic field** *H* on **distance** *r* → position of the resistance inside the sensor.

Developing a new measurement interface

Altium Designer



3D Layout Mode



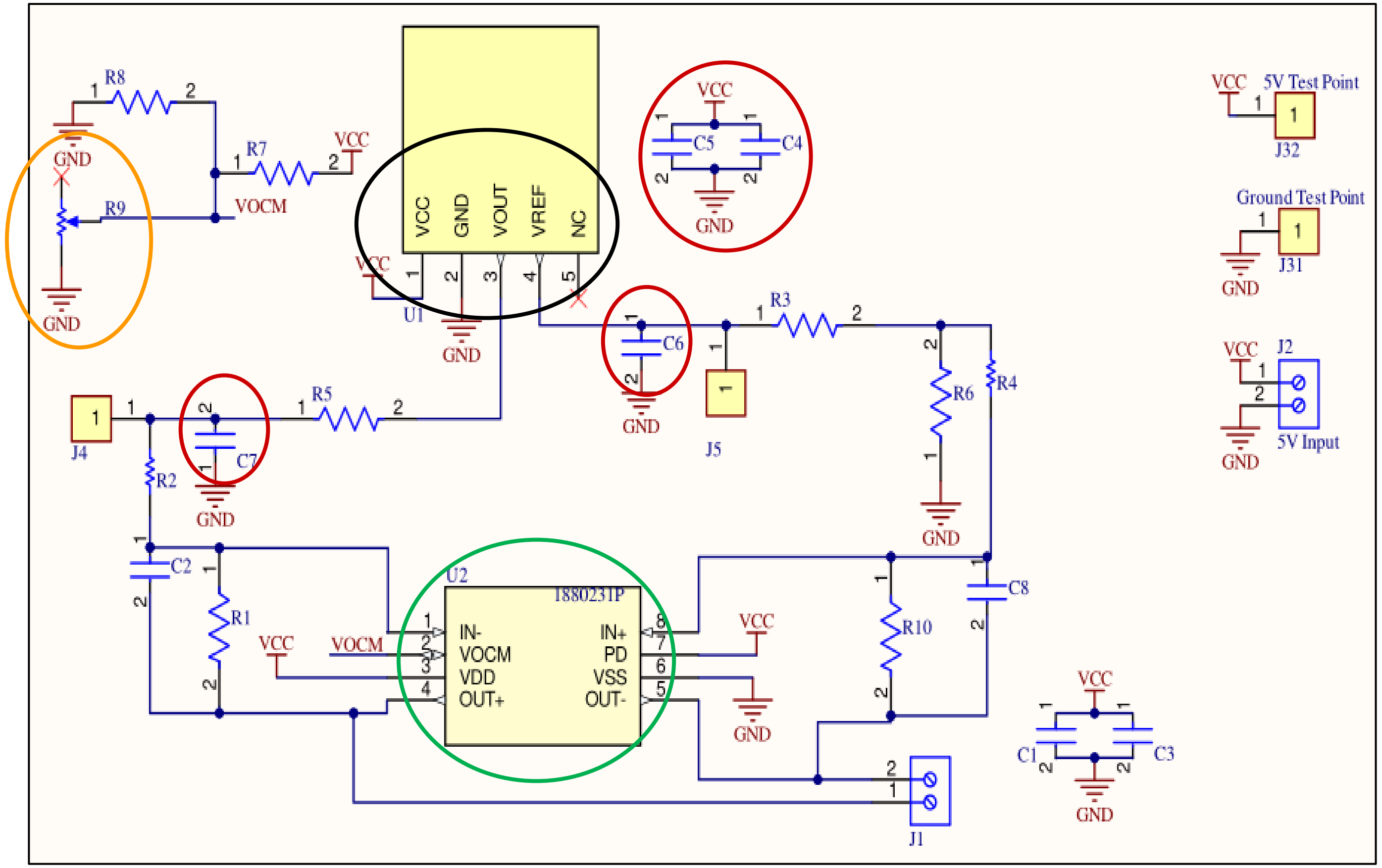
2D Layout Mode (Top Layer)

- **Printed circuit board (PCB)** for the **interface** with current sensors **STB-xxxLA/ZN**;
- allows three sensors to be tested simultaneously;
- performs **signal amplification** and **buffering.**

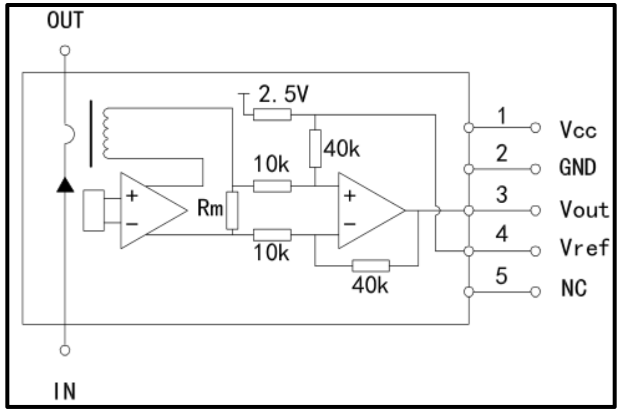
→ **Facilitates measurement procedures**

Developing a new measurement interface

Altium Designer



➢ Circuit schematic



➢ STB-xxxLA/ZN terminals

- **ICs** and resistances for (separate) amplifications of V_{out} and V_{ref};
- **potentiometer** allows change in amplification;
- most **capacitors** to filter fluctuations in the signals.

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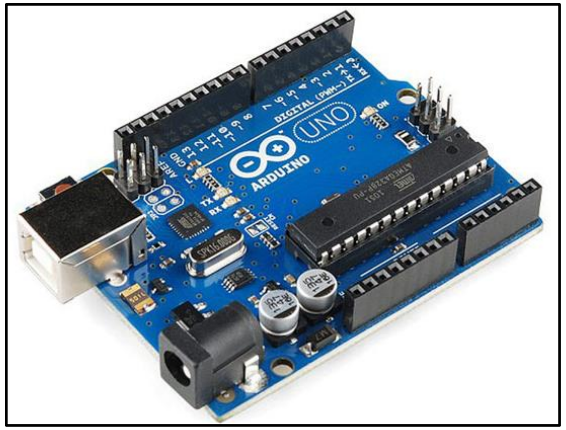
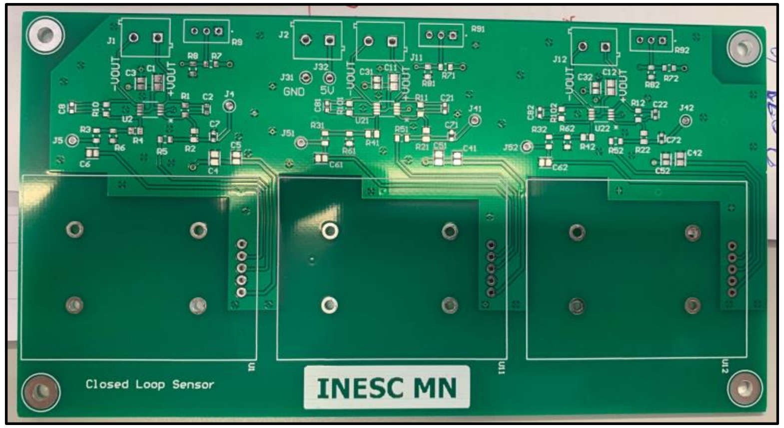
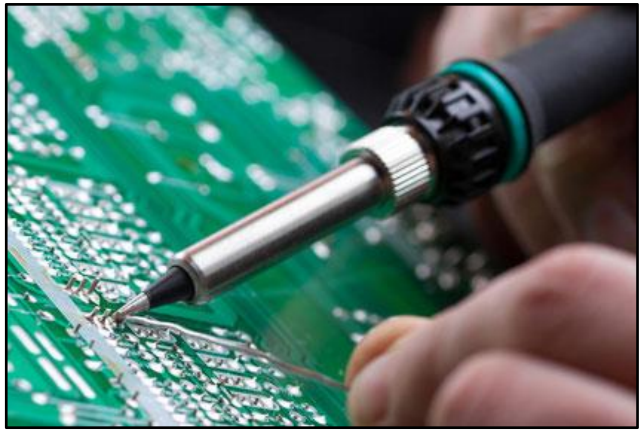
Conclusion

- **Current sensing** demand continues to expand → **magnetoresistive sensors** as an alternative to conventional methods;
- State-of-the-art current sensors using **TMR** and **GMR** technologies were characterized:
  - ❑ MPW5 (N88TJ152) in the linear range (saturation not reached);
  - ❑ INSPECT (GMR ECP 1.0) with apparent hysteresis and higher precision.
- Characterization of **STB-200LA/ZN** current sensor (TMR technology) in the linear range; 3D model developed for use with fixed distance; PCB designed for measurement interface;
- **Regarding the work on advanced current sensors, the possibilities appear to be endless…**







…even more to be done!