EVALUATION OF HYSTERESIS OFFSET ERROR IN HALL-EFFECT CURRENT SENSORS USING SOFT FERROMAGNETIC CONCENTRATOR CORES

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INTRODUCTION

The technique of measuring busbar current with a surrounding soft ferromagnetic concentrator core is common knowledge. For high-current measurement (above 200 A), Allegro recommends using a linear IC, such as the A1365, A1367, or ACS70310, in conjunction with a ferromagnetic core (Figure 1).

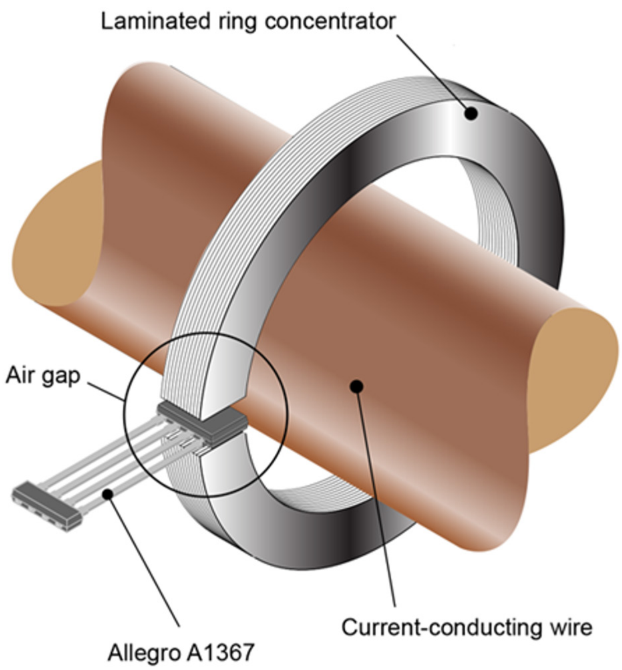

Figure 1: Typical high-current sensing system with magnetic core and Allegro A1367

Soft ferromagnetic cores are used to amplify the magnetic signal measured by the sensor, improving accuracy and resolution. Coupling factor CF is the ratio between the magnetic field B measured by the linear IC in the air gap and the current I flowing in the conducting wire. Typical coupling factors of core-based current sensors are in the range of a few gauss per ampere. Note that only open-loop systems are considered in this document.

Equation 1:

$$CF = \frac{B}{I}$$

For more details about core design, refer to “Guidelines for Designing a Concentrator for High-Current Sensing Applications with an Allegro Hall-Effect Sensor IC”, available on the Allegro website [1].

However, one disadvantage of using ferromagnetic material as a concentrating core is the magnetic hysteresis. Magnetic hysteresis means that the magnetization state of the core depends on its magnetic history. Only brief explanations of this will be given in this document; more detailed explanations can be found in “Hysteresis Mitigation in Current Sensor ICs Using Ferromagnetic Cores”, available on the Allegro website [2].

[1] https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/current-sensor-concentrator.

[2] https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/hysteresis-mitigation-in-current-sensor-ics-using-ferromagnetic-cores.

Figure 2 represents the magnetic behavior of the same arbitrary soft ferromagnetic concentrator core material in two situations. In Figure 2, the x axis is the magnetic field, proportional to the current flowing in the busbar.

In the first situation, the core is magnetized by a sufficiently high current at low frequency. It is assumed that the core is initially unmagnetized (state 0). At high positive current, the magnetization reaches saturation (state I). When the current returns to zero, the core retains a remanent magnetization; the magnetization is no longer zero at zero field (i.e. zero current) (state II). Hence, the sensor placed in the air gap will measure a magnetic field while the current in the conducting wire is zero; this is the hysteresis offset. Applying a high opposite current leads the core to the negative saturation state (state III). At zero current (state IV), the magnetization is again different from state 0 and state II. Note that in Figure 2, the hysteresis is highly exaggerated, compared to the real behavior of concentrator cores, to make the phenomenon clearly visible. The tendency of a ferromagnetic material to have high or low hysteresis depends on the coercive field Hc, defined as the remanent field inside the unmagnetized material.

It should be clear that the first situation described above is not desired in a current sensor application because of the core saturation. In an application, the core is normally used in its linear range (overcurrent excepted). Thus, in the second situation, the material follows the red cycle of Figure 2. In this case, the material hysteresis still introduces an offset of the sensor output, but smaller in theory (state V and state VI).

In this application note, the impact of magnetic core hysteresis on current measurement accuracy is evaluated, especially the impact on the measured offset variation.

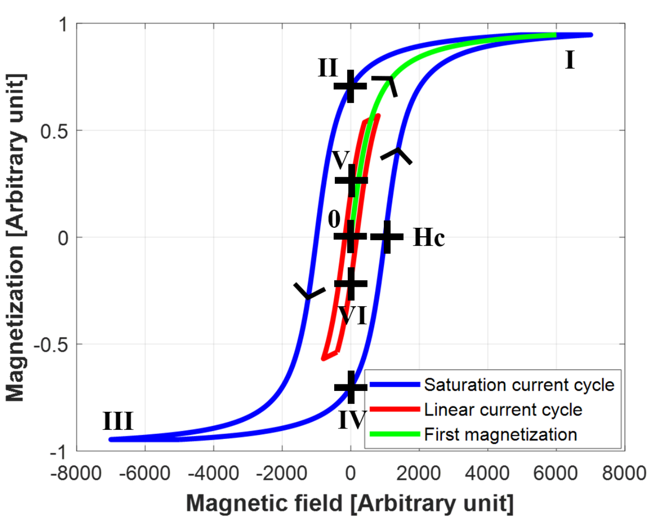

Figure 2: Schematic behavior of a soft ferromagnetic material

MEASUREMENT PROTOCOL

A low frequency (<1 Hz) triangular waveform current is set in the conducting wire (Figure 3). Two different peak currents are used: $\mathrm{I_{sat}}$ and $\mathrm{I_{lin}}$. $\mathrm{I_{sat}}$ is chosen such that the core reaches deep saturation; the core behavior follows the blue curve of Figure 2. A linear IC is placed inside the air gap and the magnetic field is measured in state II and IV. These measurements are called $\mathrm{B_{II}}$ and $\mathrm{B_{IV}}$. $\mathrm{I_{lin}}$ is chosen such that the core stays in its linear range; the core behavior follows the red curve of Figure 2. The magnetic field is measured in states V and VI. These measurements are called $\mathrm{B_V}$ and $\mathrm{B_{VI}}$. Note that the initial core magnetic state is unknown, but this is not an issue since the core is forced to the desired state with the triangular current. All measurements in this document have been performed at room temperature.

The field hysteresis offset, with saturation current, is given by:

Equation 2:

$$B_{hyst,sat} = \frac{|B_{II} - B_{IV}|}{2}$$

This can be converted to current measurement error due to hysteresis, thanks to the given core coupling factor CF.

Equation 3:

$$I_{hyst,sat} = \frac{B_{hyst,sat}}{CF}$$

And similarly, with linear current:

Equation 4:

$$B_{hyst,lin} = \frac{|B_V - B_{VI}|}{2}$$

Equation 5:

$$I_{hyst,lin} = \frac{B_{hyst,lin}}{CF}$$

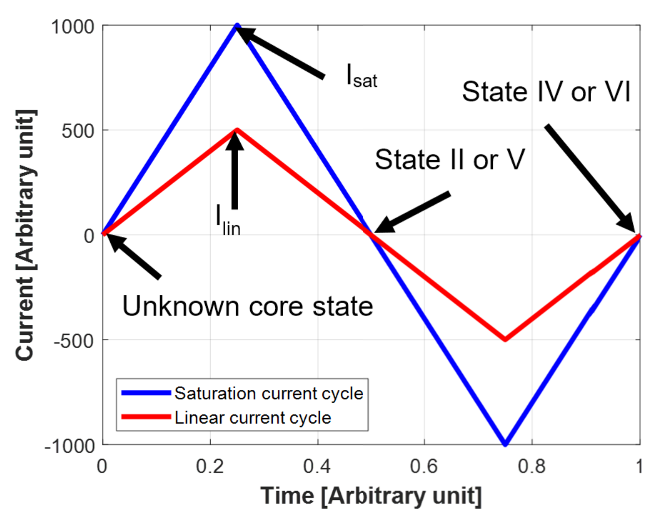

Figure 3: Current waveforms

FERROMAGNETIC CORE DESCRIPTIONS

Various concentrator cores have been measured, with different shapes, materials, volumes of material, air gaps (see Figure 4), etc. In total, 17 cores have been measured, representing 11 different variations. All cores are listed in Table 1.

Cores #1 to #7 have been specifically manufactured for this analysis (Figure 4 and Figure 5). Cores #8 to #11 are customer cores currently used in current sensing applications.

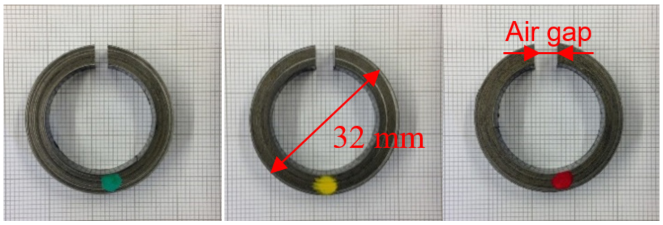

Figure 4: Photos of cores #1, #2, and #3 (from left to right)

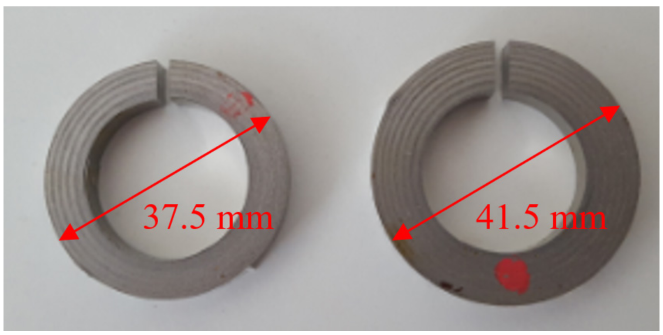

Figure 5: Photos of cores #5 and #7 (from left to right)

About the core material, two materials are considered: FeSi (grain-oriented (GO) electrical steel) and FeNi. FeSi material is the usual material used in core-based current sensors because of its high relative permeability, high saturation level, and fairly low cost (Table 2). FeNi has even higher relative permeability but much lower saturation level, which makes it not suitable for high-current sensing application. However, it is considered in this analysis because it has a much lower coercive field; it makes visible the correlation between hysteresis offset and coercive field. Also, FeNi cores are typically at least two times more expensive than FeSi cores.

Table 2: Typical magnetic characteristics of core materials

Material	Typical Relative Permeability	Typical Polarization at Saturation (T)	Typical Coercive Field (A/m)
FeSi GO	>10000	1.8	50
FeNi	>50000	0.7	1

All cores are laminated. Three different sheet thicknesses are considered, from 0.1 to 0.3 mm. Lamination is used to reduce eddy current effect due to AC current. For more details about core lamination, refer to "High-Current Measurement with Allegro Current Sensor IC and Ferromagnetic Core: Impact of Eddy Currents", available on the Allegro website [3].

Two general shapes of core are considered: ring shape, as in Figure 4 and Figure 5, and rectangle shape, as in Figure 6, with and without fillet on edges.

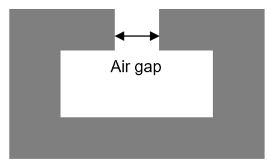

Figure 6: Core with rectangle shape

Table 1: Core descriptions

Core ID	Number of Cores Measured	Core Shape	Material	Sheet Thickness (mm)	Air Gap (mm)	Total Magnetic Volume (mm^3)	Nominal Coupling Factor (G/A)
#1	2	Ring	FeSi	0.1	3	~2700	4.4
#2	1	Ring	FeSi	0.1	4	~2700	3.0
#3	1	Ring	FeSi	0.1	5	~2700	2.4
#4	2	Ring	FeNi	0.1	2	~3500	6.1
#5	2	Ring	FeNi	0.2	2	~3500	6.1
#6	2	Ring	FeNi	0.1	2	~5000	6.1
#7	2	Ring	FeNi	0.2	2	~5000	6.1
#8	2	Rectangle	FeSi	0.3	5	~6500	2.4
#9	1	Rectangle	FeSi	0.3	7	~4300	1.7
#10	1	Ring	FeSi	0.3	3	~2600	3.9
#11	1	Ring	FeSi	0.3	6	~2000	2.0

[3] https://www.allegromicro.com/en/insights-and-innovations/technical-documents/hall-effect-sensor-ic-publications/an296162_a1367_current-sensor-eddy-current-core.

MEASURED HYSTERESIS OFFSET

First, in Figure 7, the field hysteresis offset B_{hyst} is plotted versus the coupling factor for both the linear and saturation current cycles and for FeSi cores only. There is a clear trend showing that larger coupling factors lead to higher field hysteresis offset. One can also notice that the linear and the saturation current cycles lead to very similar field hysteresis offsets. States II and V (or states IV and VI) appear very similar.

However, Figure 8 shows that the actual current measurement hysteresis error does not depend on the FeSi core properties (dimensions, air gap, shape, etc.). Indeed, this plot represents the current hysteresis offset I_{hyst} versus coupling factor, which appears to be more or less constant around 2 A error for all cores. The current hysteresis offset only depends on the coercive field of the material and not on the core dimensions; nothing can be done to the core dimensions to reduce the current measurement error due to the magnetic hysteresis. This means that the only way to reduce the current measurement error due to the material hysteresis is to use a material with a very low coercive field.

Figure 9 indicates that the current hysteresis offset is negligible in FeNi cores; the eight measured FeNi cores have a worst-case current hysteresis offset smaller than 0.1 A. This was expected based on the very low coercive field of FeNi material compared to FeSi (see Table 2).

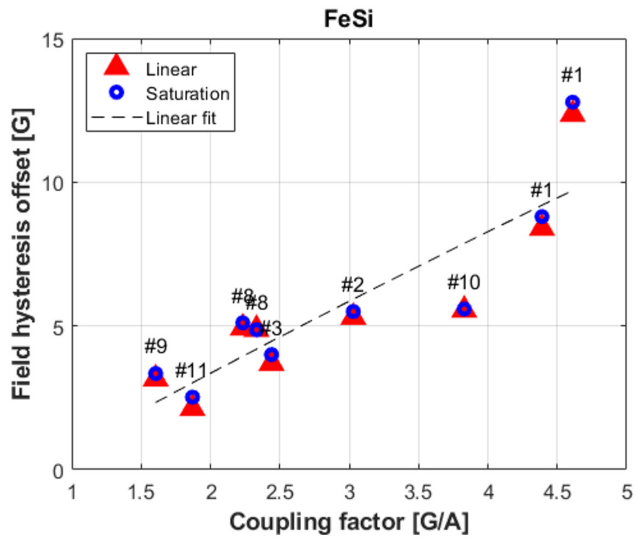

Figure 7: Field hysteresis offset versus coupling factor for FeSi cores

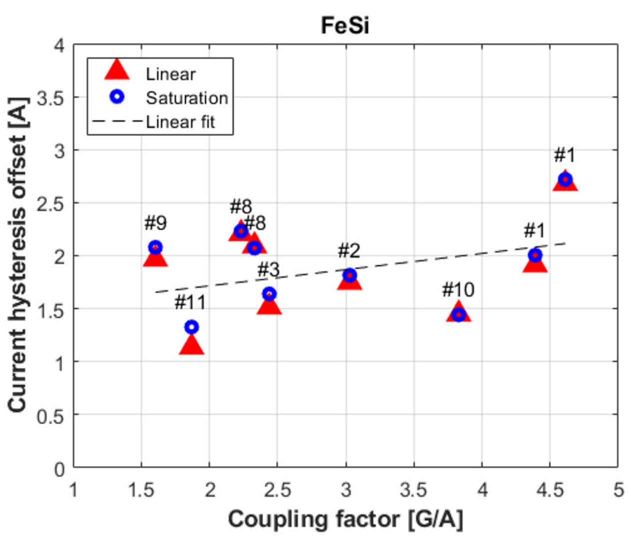

Figure 8: Current hysteresis offset versus coupling factor for FeSi cores

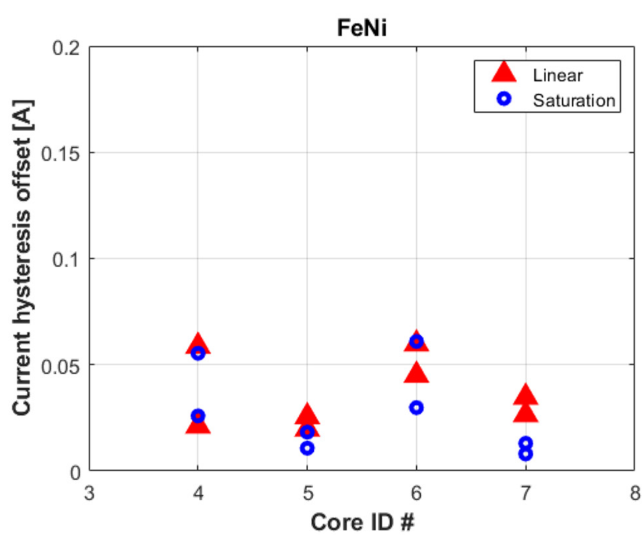

Figure 9: Current hysteresis offset for FeNi cores

CONCLUSIONS

The measurements taken on various FeSi (i.e. grain-oriented electrical steel) open-loop concentrator cores show that the current measurement offset error induced by the magnetic material hysteresis is typically ±2 A, whatever the core geometry (air gap, shape, dimensions, volume, and sheet thickness) or coupling factor. This error is related to the FeSi material coercive field.

Therefore:

- The dimensions of a FeSi concentrator core cannot be optimized to reduce the hysteresis offset.
- Any current sensor application using FeSi concentrator core has its accuracy limited to ±2 A.

The relative impact of the core hysteresis is much lower when higher currents are measured; the relative error due to the core hysteresis would be ±1% for a ±200 A application, while it would only be ±0.2% for a ±1000 A application.

If one wants to reduce the hysteresis offset, a material having a smaller coercive field should be considered, such as the FeNi. Measurements taken on FeNi cores show a current measurement offset error induced by the magnetic hysteresis smaller than ±0.1 A. However, since saturation starts much earlier with FeNi, this improvement is at the cost of the maximum current that can be measured. In addition, FeNi cores are significantly more expensive than FeSi cores.

Allegro engineers can assist customers in designing the best magnetic core (dimensions and material) for their application, depending on current requirements. Contact your local Allegro MicroSystems technical center for assistance.

Revision History

Number	Date	Description	Responsibility
–	February 19, 2020	Initial release	Y. Vuillermet