NONINTRUSIVE CURRENT-SENSING USING TMR: A COMPARISON BETWEEN TMR SENSORS, SENSE RESISTORS, HALL-EFFECT SENSORS, AND CURRENT TRANSFORMERS

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ABSTRACT

As the demand for current sensing continues to increase and the applications become diverse, the need for a universal, accurate, and cost-effective current sensor is clear. Circuit designers have various options for current measurement. These options differ in the underlying technology of the sensor and in the design and recommended implementation of the manufacturer.

It can be daunting, or at least resource consuming, to select the best current sensor that fits the design constraints in terms of: accuracy; isolation and overall safety, both of the circuit and the user; power consumption; power loss (heat dissipation), etc.

As a well-established technology, tunnel magnetoresistance (TMR) offers a set of features that allows for its use as a current sensor. Specifically, the Allegro CT100 family of linear TMR sensors can be used as a surface-mount technology (SMT), nonintrusive device with great linearity and thermal performance.

INTRODUCTION

TMR technology is widely used in different applications: hard drives, memory devices, magnetic sensors. The first scientific papers were published during the 1990s and a Physics Nobel prize was awarded to Albert Fert and Peter Grünberg for their work on giant magnetoresistance (GMR) technology, which was the precursor to TMR technology.

For a more in-depth discussion about xMR technologies, refer to From Hall-Effect to TMR (Allegro application note AN116).

Allegro advancements in TMR technology, including semiconductor integration on standard wafers and advanced nodes, allow fulfillment of the ever-increasing demand for small, reliable, and cost-effective magnetic sensors, including magnetic latches, angle sensors, and speed and direction sensors.

At its core, the resistance, R, of a TMR sensor changes under a changing external magnetic field, H. This is referred to as the R(H) curve. The response of the TMR sensor (meaning its R(H) curve) can be adjusted depending on the end application. Hysteresis, saturation fields, and sensitivity are examples of the parameters that can be set differently for different products.

The TMR sensor implemented in the CT100 device has a ratiometric linear output. It is optimized to have zero-hysteresis, saturation fields at ±20 mT, and a linearity error of less than ±1% over the operating range.

The goal of this paper is to help circuit designers understand the benefits and shortcomings of the CT100, especially compared to existence alternatives.

CURRENT-SENSING TECHNOLOGIES

There are three common current-sensing techniques that use a sense resistor, the Hall-effect, or a current transformer. A comparative analysis of the current-sensing technologies discussed in this paper is summarized in Table 1.

Table 1: Comparative Table of Widely Used Current-Sensing Technologies

Current Sensor	Accuracy	Isolation	Insertion Loss	Power Supply	Bandwidth	Cost
Sense Resistor	±3 to ±5%	No	High	No	DC to 10 MHz	Low
Contact Hall-Effect	±1 to ±5%	Medium	Medium	High	DC to 1 MHz	High
Contactless Hall-Effect	±5 to ±10%	Yes	Zero	High	DC to 100 kHz	Medium
Current Transformer	±1 to ±5%	Yes	Zero	No	50 Hz to 1 MHz	Medium
Allegro CT100	±0.5%	Yes	Zero	Low	DC to 1 MHz	Low

Sense Resistor

Using a resistor to measure current is the easiest method of current sensing. This method uses:

Equation 1: Ohm's law

$$V = I \times R,$$

where V is the voltage across the resistor, R is the ohmic value of the resistor, and I is the current flowing in the resistor. Sense resistors are widely used because they are typically very low cost and easy to implement in a design. However, sense resistors present major drawbacks.

A sense resistor is not isolated: It requires additional circuitry to achieve standardized isolation requirements. This lack of isolation also leads to power loss, typically in the form of heat; this influences the resistance level of the sense resistor, which in turn reduces the accuracy of the sense resistor. To reduce these losses, designers can choose power resistors, although these are typically not compatible with surface-mount technology (SMT) and are costlier. Although use of a lower resistance value can reduce the power losses, this also reduces the voltage to drop across the resistor (due to Ohm's law), which leads circuit designers to implement an additional operational amplifier. Finally, the series inductance of sense resistors limits their use in high-frequency designs.

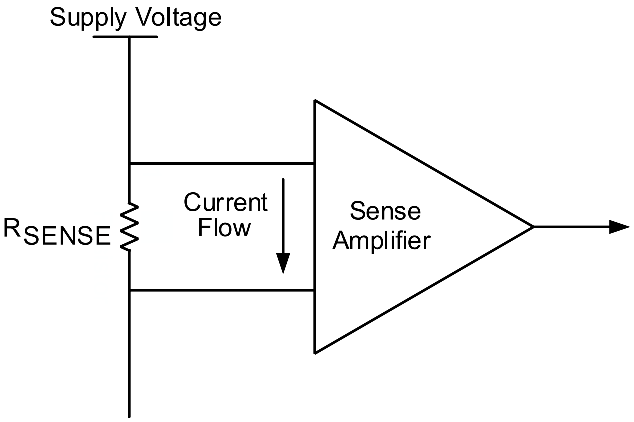

Figure 1: Sense Resistor, Simple Circuit Implementation

Hall-Effect Sensor

The Hall effect was first discovered in 1879 and was implemented in semiconductors during the 1960s. For a more in-depth discussion about Hall-effect technology, refer to From Hall-Effect to TMR (Allegro application note AN116). There are a number of available current sensors today based on this technology. These sensors can be divided into two groups: contact and contactless.

Contact Hall-effect devices include a current-carrying conductor (CCC) that drives the current inside the package of the integrated circuit (IC). Because the CCC and the Hall-effect IC are not physically connected, these devices offer some voltage isolation, typically in the range of 1 kV to 5 kV. Typically, the manufacturer would precalibrate this type of sensor to avoid any change in performance due to the physical mounting of the CCC with regard to the IC. While this solution offers voltage isolation, the CCC represents a resistance on the current path. This leads to similar, however smaller, power losses as a sense resistor. As an obvious note, the shape and size of the CCC limits the maximum current: circuit designers need to carefully assess their peak currents and to use different devices (P/Ns) to measure different current levels.

Contactless Hall-effect devices require an internal or external flux guide (i.e., a magnetic-field concentrator) that helps channel the magnetic-field lines generated by the flowing current. Because current does not flow in the package, this solution does not have any insertion loss. However, the addition of a toroid or other flux guide solution adds implementation hurdles. Also, flux guide impacts measurement accuracy due to the added hysteresis.

In general, disadvantages of Hall-effect sensors include: the high current consumption, temperature performance, especially of DC offset, and cost.

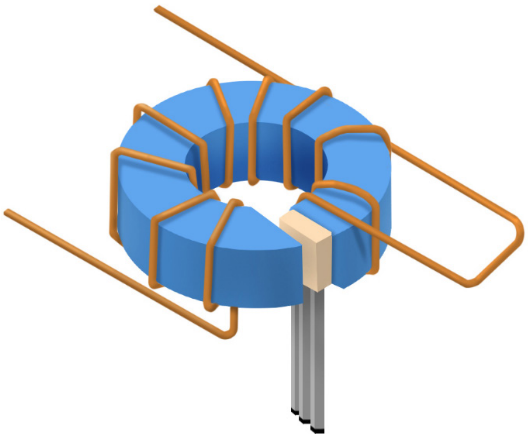

Figure 2: Contactless Hall-Effect Sensor with Toroid Concentrator

Current Transformer

Current transformers generate an alternating current that is proportional to the primary current. The ratio between the number of turns in the primary and secondary windings defines the current output of the current transformer according to:

Equation 2:

$$I_s = I_p(N_p/N_s),$$

where I_S is the secondary current (output current), I_P is the primary current, and N is the number of turns.

Current transformers (CTs) can include a soft core (i.e., a ferromagnetic core), which reduces the overall size of the CT, albeit with additional hysteresis issues that system designers consider in metering applications. A burden resistor is added to close the CT circuit and provide a ratiometric voltage.

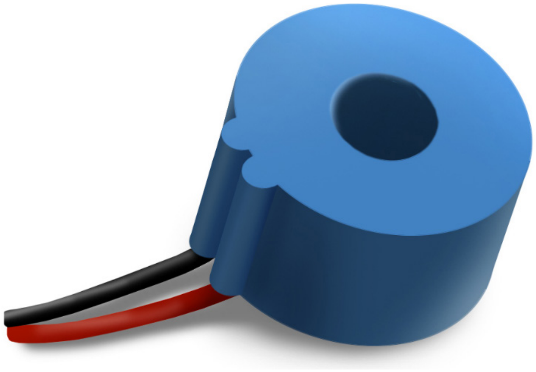

Figure 3: Current Transformer

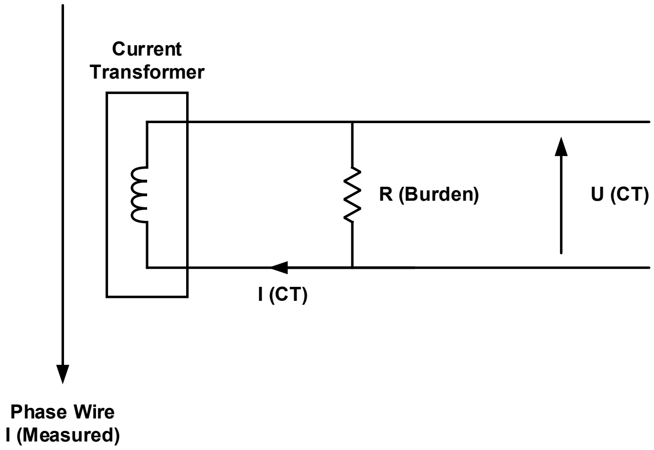

Figure 4: Current Transformer with Burden Resistor to Generate a Ratiometric Voltage

CT100: LINEAR TMR SENSOR

The CT100 is a linear TMR sensor that features four TMR elements configured as a full bridge. The CT100 consists only of the full-bridge TMR sensor and electrostatic-discharge (ESD) protection. It does not include any active CMOS circuitry.

Sweeping the external magnetic field shows the characteristic curve of the sensor. The curve does not show any hysteresis within the operating range.

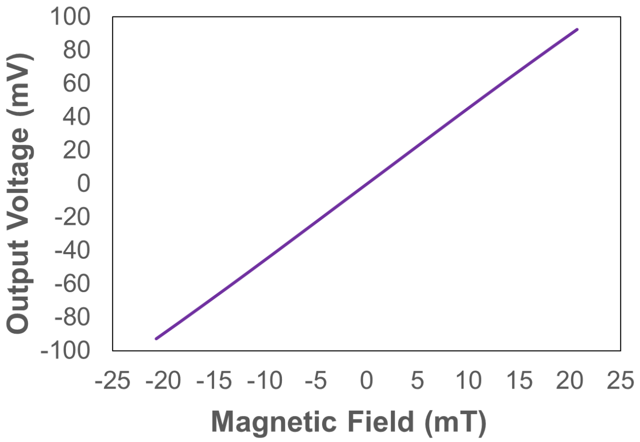

Figure 5: CT100 Output Voltage vs. Magnetic Field

Linearity

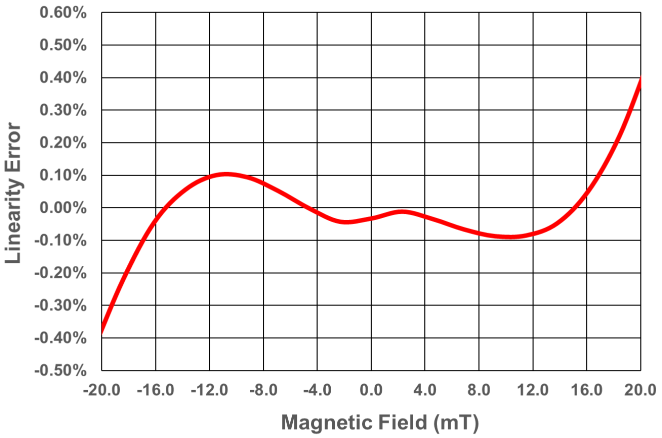

Figure 6: CT100 Linearity Error vs. Magnetic Field

Offset

The offset referred to in this paragraph is the quiescent output voltage of the sensor. This is also called the DC offset. As previously mentioned, the CT100 does not include any CMOS circuitry capable of adjusting the offset. The offset of the CT100 is solely determined by the balance of the four TMR elements that form its full bridge.

Temperature

The CT100 does not require active temperature compensation. The TMR full-bridge configuration allows the CT100 to achieve extremely stable magnetic performance over a wide temperature range.

The gain or sensitivity change over temperature is shown in Figure 7. There is very little difference between the sensitivity at each temperature. Offset-voltage change of the CT100 over the temperature of –40°C to 125°C is minimal, as illustrated in Figure 8.

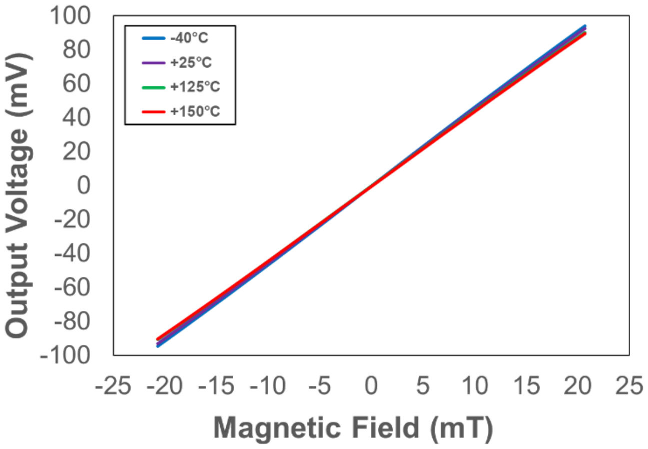

Figure 7: CT100 Linearity Error vs. Magnetic Field vs. Temperature

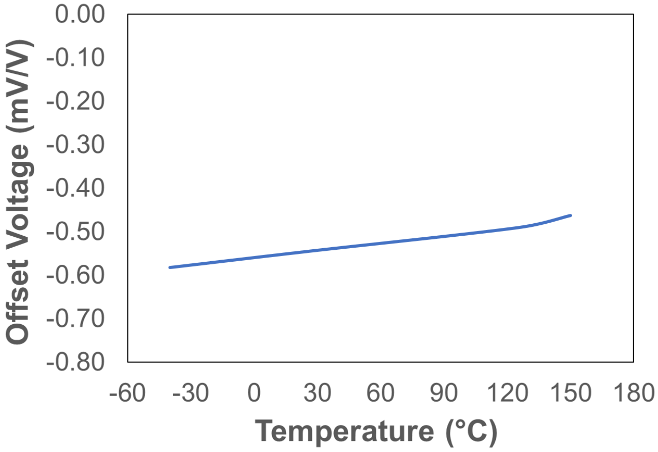

Figure 8: CT100 Offset Voltage vs. Temperature

Power Draw

The CT100 consists only of the full-bridge TMR sensor and ESD protection. Due to the lack of active CMOS circuitry, the CT100 power draw is solely determined by the voltage applied to the full bridge.

The full-bridge resistance of the CT100 is typically 30 kΩ: Applying a 3 V supply yields 100 µA current draw.

Noise

The CT100 is able to achieve low noise figures without the use of any circuitry. Advancement in magnetic materials and design allows the CT100 to achieve 624 $nV_{RMS}/\sqrt{Hz}$ at 10 Hz. The noise performance of the CT100 from 0.1 Hz to 10 kHz is illustrated in Figure 9.

Circuit designers can choose to implement a simple RC filter to attenuate any frequencies that are not of interest.

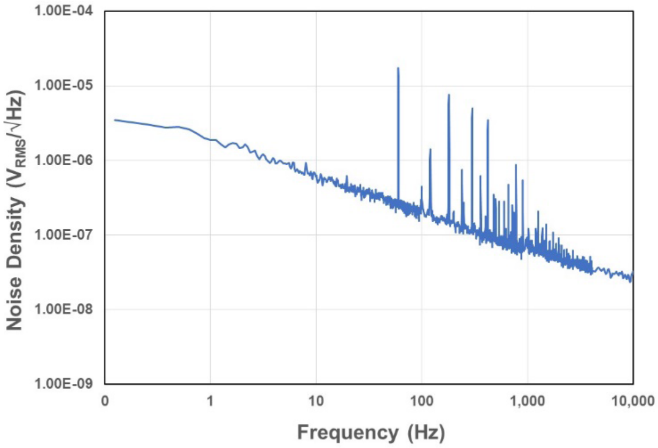

Figure 9: CT100 Noise Performance

Current Overload

A current overload translates to a strong magnetic field applied to the sensor. If this magnetic field is higher than the sensor operating range of ±20 mT, it drives the sensor outside of its linear range. This, however, does not damage the sensor. The sensor resumes normal operation as soon as the external magnetic field returns to within the operating range.

CONCLUSION

Current-sensing demand continues to increase. The applications and use cases continue to expand. Electrical engineers can choose from multiple technologies and manufacturers. However, each technology comes with its limitations and compromises.

The CT100 offers designers clear advantages that allow them to avoid previous compromises in their designs. The CT100 is a nonintrusive, precise, cost-effective current sensor.

Allegro TMR sensor advancements in design, magnetic development, process integration, testing, etc., have delivered the intended results. TMR technology is gaining momentum within the semiconductor world. Allegro continues to lead, satisfying the current and emerging needs of its partners.

Revision History

Number	Date	Description	Responsibility
1	November 15, 2023	Document rebrand and minor editorial corrections	J. Henry