# Non-Intrusive Current-Sensing Using TMR: A Comparison Between TMR Sensors, Sense Resistors, Hall-effect Sensors and Current Transformers

## Referenced Device

CT100

## 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 different options for current measurement, these options differ in the underlying technology of the sensor, they also differ in the design and recommended implementation of the manufacturer.

It can be daunting, or at least resource consuming, to decide 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 and power loss (heat dissipation), etc.

As a well-established technology, TMR (Tunnel Magneto-Resistance) offers a set of features that allows for its use as a current sensor. Specifically, the CT100 family can be used as an SMT, non-intrusive 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 on their work on GMR, which was the precursor to TMR technology.

For a more in-depth discussion on xMR technologies, please refer to AN116: From Hall-effect to TMR.

Crocus Technology's advancements in TMR technology, semiconductor integration on standard wafers and advances nodes allows it to fulfill the ever-increasing demand for small, reliable and cost-effective magnetic sensors: including, magnetic latches, angle sensors, speeds and direction sensors.

At its core, a TMR sensor's resistance 'R' will change under a changing external magnetic field 'H'. This is referred to as the R(H) curve. The response of the TMR sensor (meaning it's R(H) curve) can be adjusted depending on the end application. Hysteresis, Saturation fields, 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 short-comings of the CT100, especially compared to existence alternatives.

## Current Sensing Technologies

The three commonly used current sensing technique make use of:

- Sense resistor
- Current transformer
- Hall-effect

Table 1 summarizes a comparative analysis of the four (4) current sensing technologies discusses in this paper.

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| 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 |
| Crocus Technology CT100 | ±1% | Yes | Zero | Low | DC to 1 MHz | Low |

TABLE 1 COMPARATIVE TABLE BETWEEN WIDELY USED CURRENT SENSING TECHNOLOGIES

## Sense Resistor

Using a resistor to measure current is the easiest method of current sensing. This method uses Ohm's law

$$V = I \cdot R$$

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.

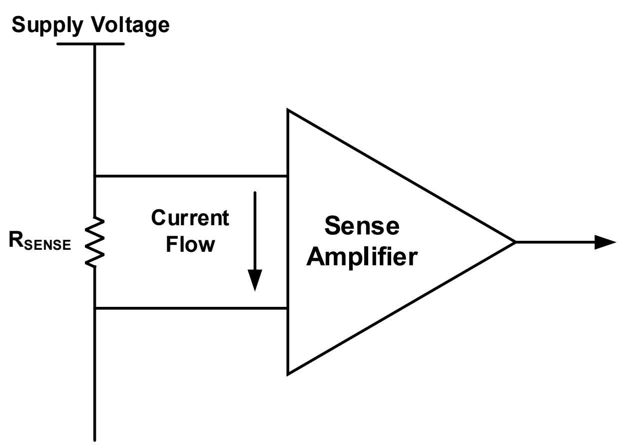


FIGURE 1. SENSE RESISTOR, SIMPLE CIRCUIT IMPLEMENTATION

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 losses. The power losses are typically in the form of heat, which influences the resistance level of the sense resistor, this in turn reduces the accuracy of the sense resistor. To reduce these losses, designers can choose power resistors that are typically not SMT compatible and are costlier. Also, a lower resistance value can reduce the power losses, this also reduces the voltage 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.

## Hall-effect Sensor

The Hall-effect was first discovered in 1879 and was implemented in semiconductors during the 1960s. Please refer to AN116 for a more in-depth review of Hall-effect technology. 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 pre-calibrate this type of sensors to avoid any change of performance due to the physical mounting of the CCC with regards to the IC. While this solution offers voltage isolation, the CCC represents a resistance on the current path. This leads to similar, however

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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 asses 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.

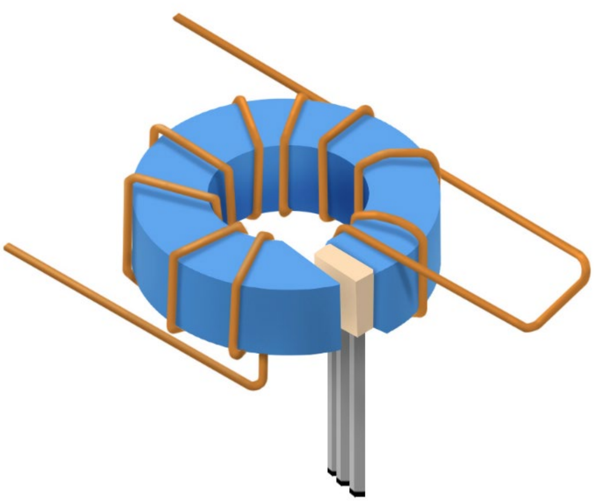

**FIGURE 2. CONTACTLESS HALL-EFFECT SENSOR WITH TOROID CONCENTRATOR**

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

## 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:

$$Is = Ip\frac{Np}{Ns}$$

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

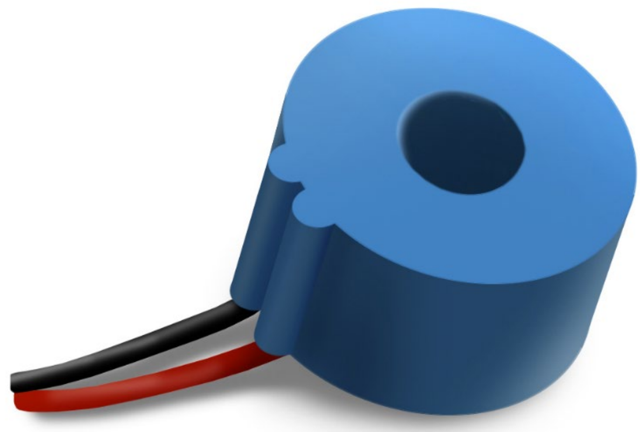

**FIGURE 3. CURRENT TRANSFORMER**

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

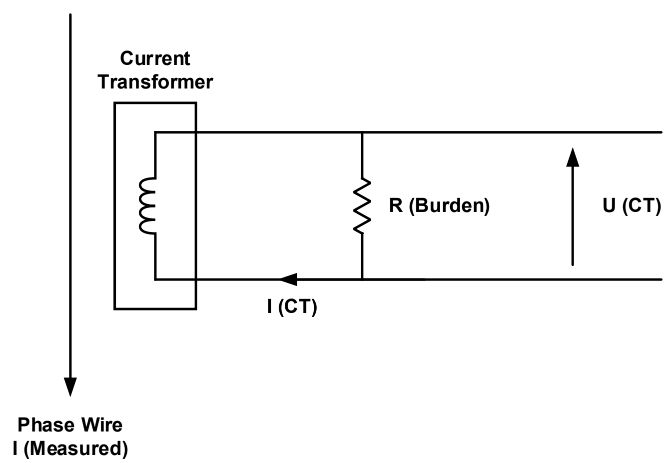


**FIGURE 4. CURRENT TRANSFORMER WITH BURDEN RESISTOR TO GENERATE A RATIOMETRIC VOLTAGE.**

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# CT100: Linear TMR Sensor

The CT100 is a linear TMR sensor that features four (4) TMR elements configured as a full-bridge. The CT100 consists only of the full-bridge TMR sensor and ESD protection, it does not include any active CMOS circuitry.

Sweeping the external magnetic field shows the characteristic curve of the sensor. The curve shows no hysteresis within the operating range.

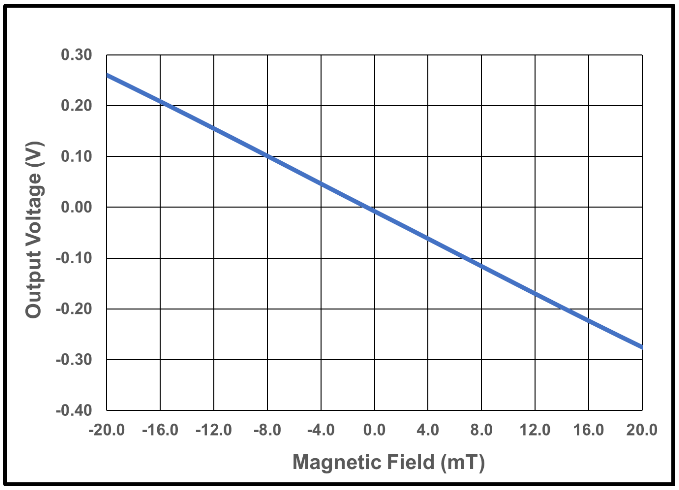


**FIGURE 5. CT100 OUTPUT VOLTAGE VS. MAGNETIC FIELD.**

## Linearity

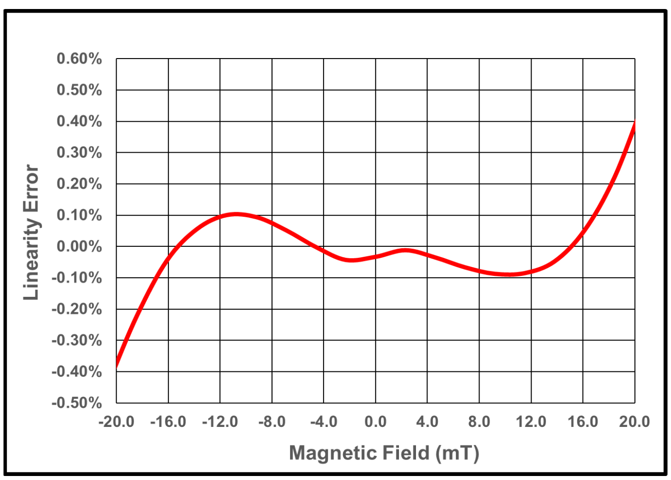


**FIGURE 6. CT100 LINEARITY ERROR VS. MAGNETIC FIELD**

## 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 (4) 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 the figure below. There is very little difference between the sensitivity at each temperature.

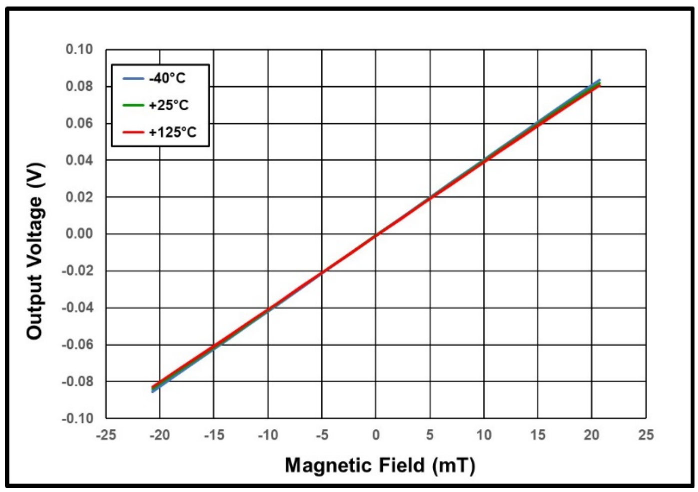


**FIGURE 7. CT100 LINEARITY ERROR VS. MAGNETIC FIELD VS. TEMPERATURE**

Offset voltage change of the CT100 over the temperature of -40°C to +125°C is minimal as illustrated in Figure 8.

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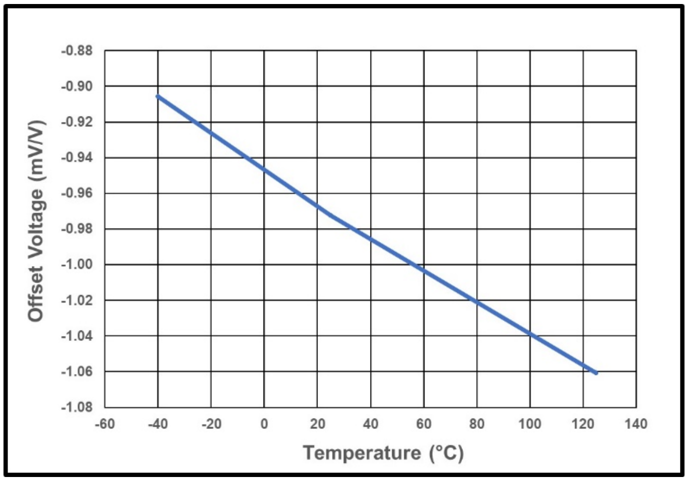


**FIGURE 8. CT100 OFFSET VOLTAGE VS. TEMPERATURE**

## 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 will yield 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. Figure 9 illustrates the noise performance of the CT100 from 0.1 Hz to 10 kHz.

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

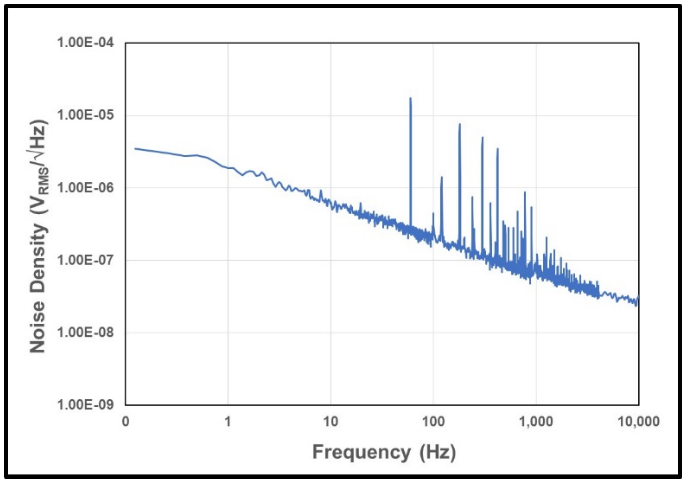


**FIGURE 9. CT100 NOISE PERFORMANCE**

## Current Overload

A current overload translates to a strong magnetic field applied to the sensor. In case this magnetic field is higher than the sensors operating range of ±20 mT, it will drive the sensor outside of its linear range. This however, will not damage the sensor. The sensor resumes normal operations as soon as the external magnetic field is back within the operating range.

# Conclusion

Current sensing demand continues to increase. The applications and uses case continue to expand. Electrical engineers have multiple technologies and manufacturers to choose from. However, each technology comes with its limitation and compromises.

The CT100 offers designers clear advantages allowing them to avoid previous compromises in their designs. The CT100 is a non-intrusive, precise and cost-effective current sensor.

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

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