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Current sensing

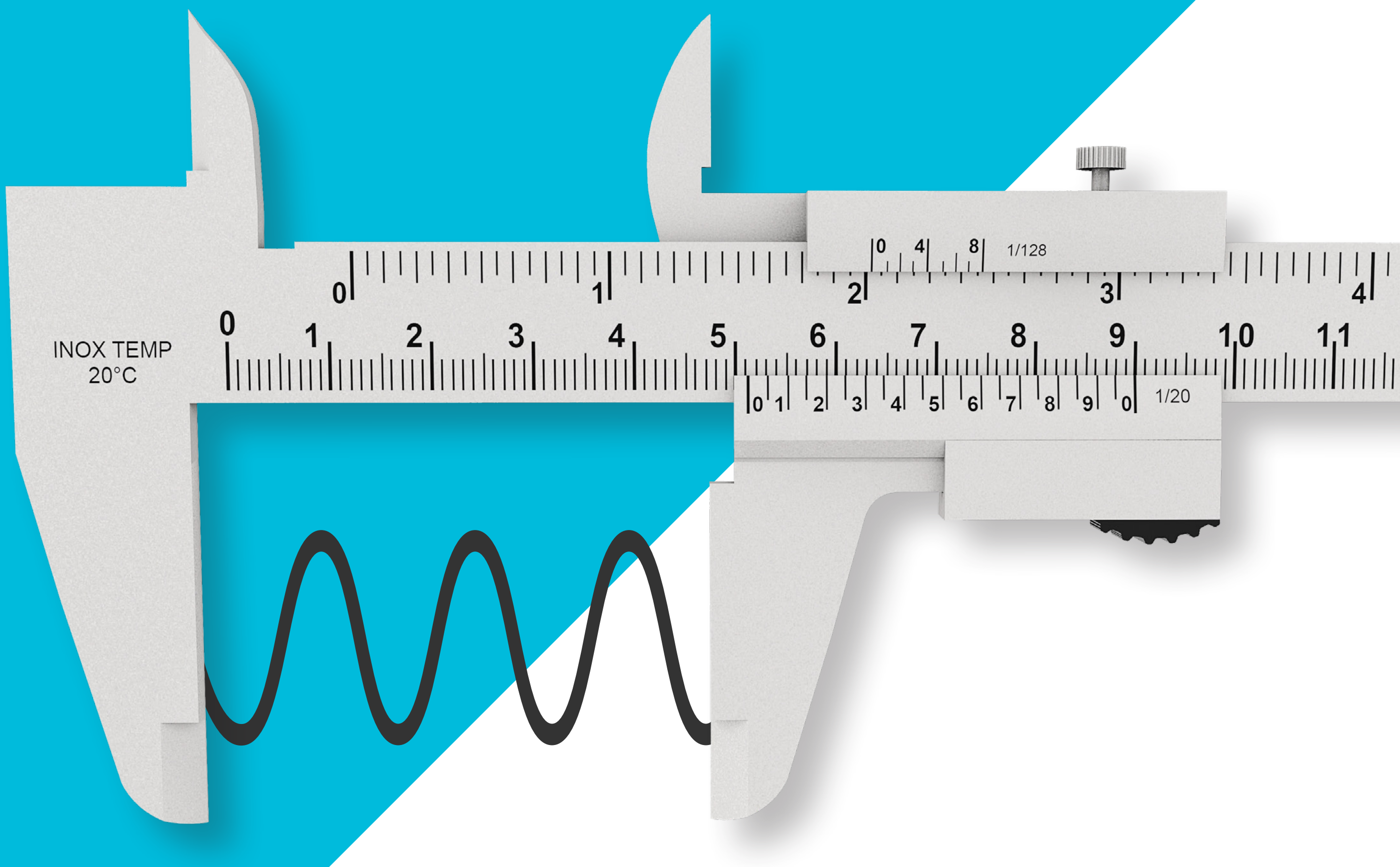

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Image: RS Components

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Current sensing

Driven by current developments in energy generation and its economical use, many electronics innovations now focus on the precision of electricity monitoring, including in the industrial sector. Photovoltaics and electromobility are just two examples of this. Whether for regulating, invoicing or monitoring purposes, it is important to determine accurate consumption and performance data. The current flow is always a key factor here. This article discusses the two main techniques used; the direct and indirect method – measuring by resistance or by magnetic readings.

Direct or shunt current sensing is based on Ohm's law and is commonly assumed to be an easy-to-master method. And that can be the case – if you take into account a few constraints.

The shunt resistor is in series with the system load and generates a voltage that is proportional to the load current (Fig. 1). It can be measured with amplifiers such as current sensing amplifiers, operational amplifiers, differential amplifiers or instrument amplifiers. This method is an invasive measurement of the current, because the shunt resistor and the measurement circuit are connected to the monitored system.

Direct sensing is typically used when galvanic isolation is not required. A resistor is usually used for load currents of less than 100 A and voltages of less than 100 V.

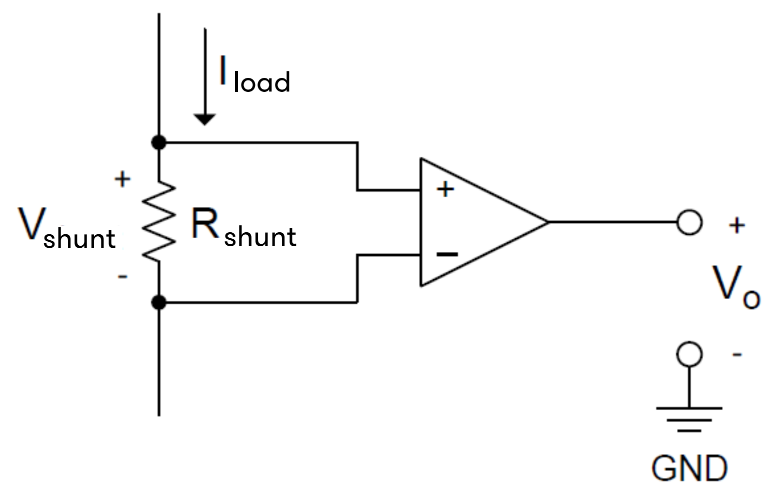

Fig. 1. The shunt resistor is in series with the system load and generates a voltage that is proportional to the load current (image: Texas Instruments)

Which shunt?

The following calculation is a key factor to consider when choosing the type of shunt resistor. It determines the maximum resistor value for an application.

The shunt resistor or R_{Shunt} is the resistor through which the load current flows in a current sensing application. Based on Ohm's law, a differential voltage called a V_{Shunt} or V_{Sense} is generated via the $R_{Shunt,}$ which is then measured by a differential amplifier.

Your choice of R_{Shunt} is mainly based on two factors – the required accuracy at minimum load current and the power dissipation at maximum load current, and the associated size and cost of the resistor.

To determine the minimum inaccuracy for a current sensing application, only the offset error of the amplifier is considered in this case. This is the dominant source of error at low load currents and at the resulting low detection voltages. The left of Fig. 2 shows that the offset error decreases as the V_{Sense} increases.

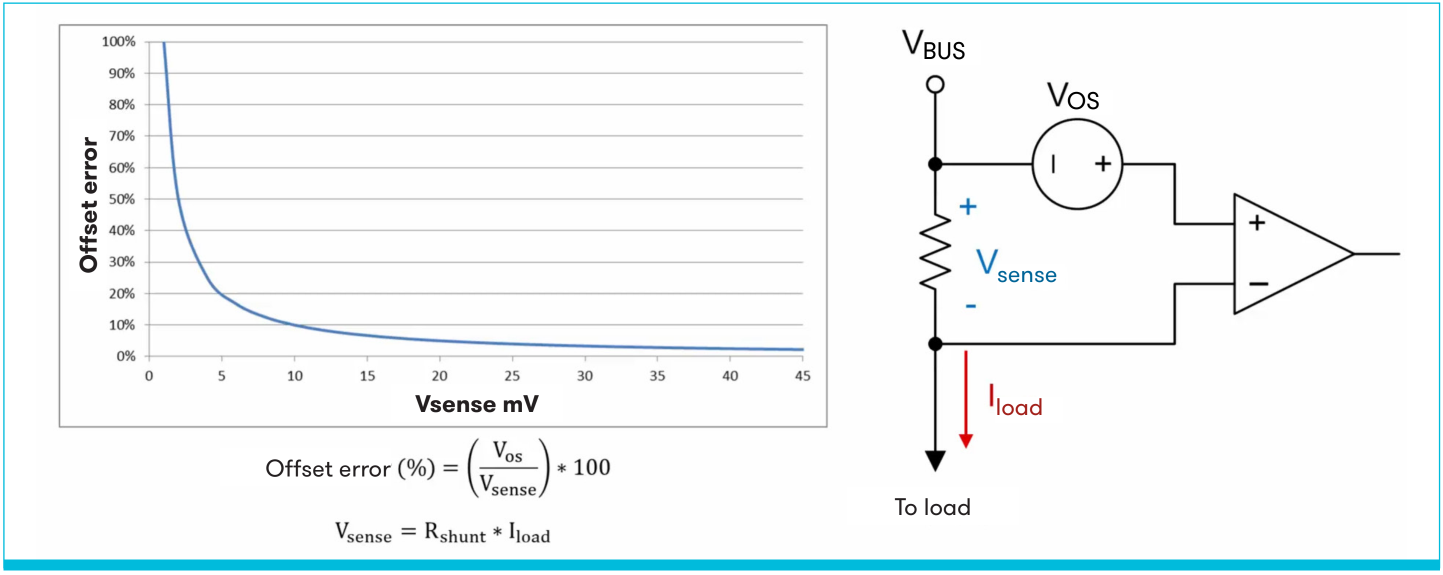

Fig. 2. The offset error decreases as the V_{Sense} increases. (Image: Texas Instruments)

The greater the voltage dropping above the shunt resistor, the more accurate the measurement due to the solid nature of V_{OS}. In other words, this fixed internal amplifier error leads to greater uncertainty as the input signal reduces.

When using our theoretical current sensing amplifier with V_{OS} = 1 mV and a V_{Sense} measuring voltage of 1 mV, we get a measurement uncertainty of 100%, as the graphic and the offset error calculation show. When the V_{Sense} is increased to 10 mV, the measurement error drops significantly to 10%. The dominant restriction at minimal current is therefore due to the offset error.

What happens at maximum current? On the left side of Fig. 3 is a diagram showing the power dissipation compared to the shunt resistor under a fixed load current (blue). The power dissipation in the shunt resistor is the product of the voltage applied to it and the current flowing through it, or the product of the shunt resistor and the square of the current flowing through it.

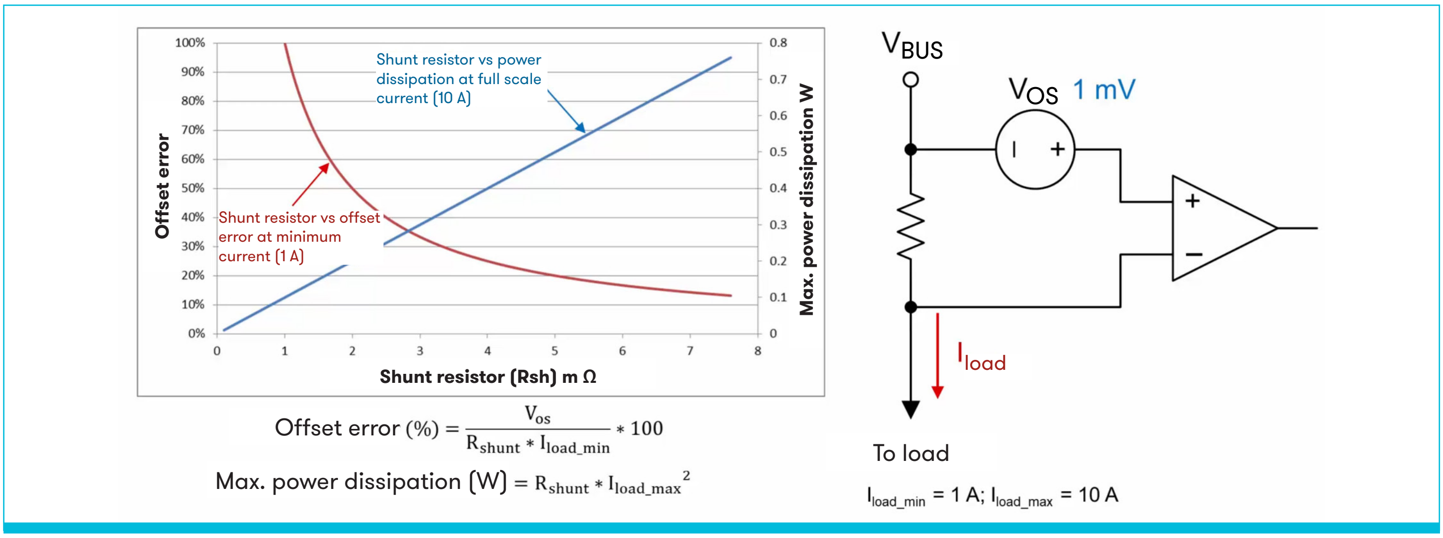

Fig. 3. There is a trade-off between maximising the accuracy at minimum current, and minimising the power dissipation at maximum current (image: Texas Instruments).

Increasing the value of the shunt resistor increases the differential voltage dropping above the resistor, thereby reducing the error caused by the amplifier offset. However, the power dissipation above the shunt resistor also increases, which can lead to heat, size and cost problems in the application.

There is a trade-off between maximising the accuracy at minimum current, and minimising the power dissipation at maximum current. An application with a minimum current of 1 A and a maximum current of 10 A uses an amplifier with V_{OS} equal to 1 mV. The red curve in the diagram in Fig. 3 shows the variation of the offset error at minimum current versus the shunt resistor for this application. The blue curve shows the variation in power dissipation at maximum current versus the shunt resistor. Increasing the shunt resistor value improves current accuracy, but also increases power dissipation. Reducing the value of the resistor reduces the power dissipation requirements, but increases the sensing error.

As a result, to find the optimal value for the shunt resistor, your selection process should take into account both the accuracy requirements of the application and the permissible power dissipation.

If you choose a 5-million-Ohm resistor for this application, the power dissipation at a maximum load current of 10 A is about 0.5 W and the inaccuracy at a minimum load current of 1 A is 20%. To improve the minimum inaccuracy to 15%, choose a shunt resistor with about 6.6 milliohms instead.

Bear in mind, however, that this will cost you about 0.66 W of power dissipation at full scale operation. A higher power dissipation requirement drives up the size and cost of the shunt resistor. This calls for a compromise, such as 5% fewer errors in exchange for 32% more power dissipation and a potential increase in resistor size and cost.

All in one

Using a current sensing amplifier with built-in current sensing resistor makes it 'simpler' to select the resistor and PCB layout. Texas Instruments INA250, INA253, and INA260-ICs have a current sensing resistor built into the same housing as the current sensing amplifier. Connections to the current sensing resistor are optimised to achieve the best measurement accuracy and temperature stability.

INA250 and INA253 are current sensing amplifiers with an analogue output, while INA260 is a digital sensor that outputs current, power and voltage through a System Management Bus (SMBus) interface.

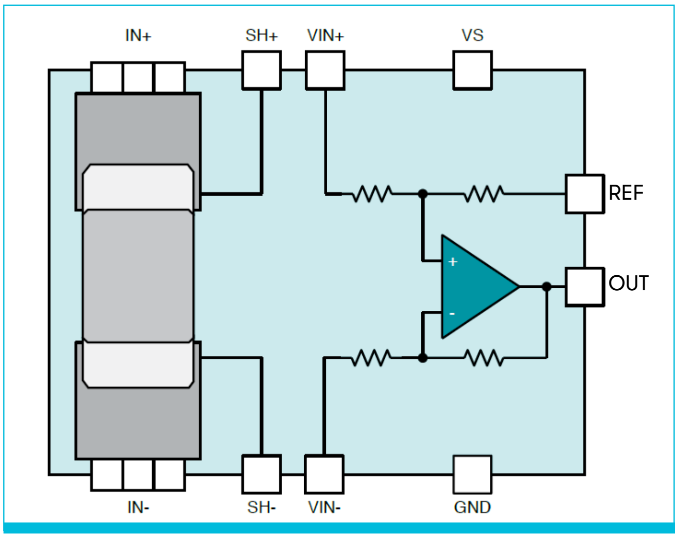

Fig. 4. Texas Instruments [INA250](INA250) – current sensing amplifier with integrated current sensing resistor (image: Texas Instruments).

Fig. 4 shows the block diagram of the INA250. This IC offers external connections so you can filter the measuring voltage or connect the unit directly to the current sensing amplifier. The amplification of the amplifier element is optimised so that the error of the overall system gain equates to the use of a 0.1%-sensing resistor or better. The integrated shunt technology used in the INA250 can tolerate currents of up to 15 A. The chip has a maximum overall system amplification error rate of 0.3% at room temperature and 0.75% over the temperature range of -40°C to 125°C. The internal connections to the current sensing resistor are in the housing and calibrated for each IC, to eliminate deviations caused at the resistor connection points.

Magnetic current sensing

Indirect or magnetic current sensing is based on Ampere's law, which states that the magnetic field in the space around a conductor is proportional to the electric current flowing through that conductor. By placing a magnetic sensor (e.g. a Hall sensor, see Fig. 5) near the live conductor, a voltage is generated above the sensor that is proportional to the magnetic field detected by the sensor.

This method allows a non-invasive sensoring, whereby the measuring circuit is not electrically connected to the monitored system. This makes magnetic current sensing an excellent choice for high voltage or dynamic current measurement settings. In the past, indirect current sensing was typically only used to measure currents of 100 A or more. The sensors were relatively expensive and not conducive to detecting currents on a PCB. It would also often require a certain degree of magnetic design, using magnetic cores, for example, to dampen or condense the magnetic flux 'seen' by the sensor. However, advances in technology and price reductions have led to devices such as in-housing magnetic current sensors. These are relatively inexpensive and well suited for lower currents on a PCB.

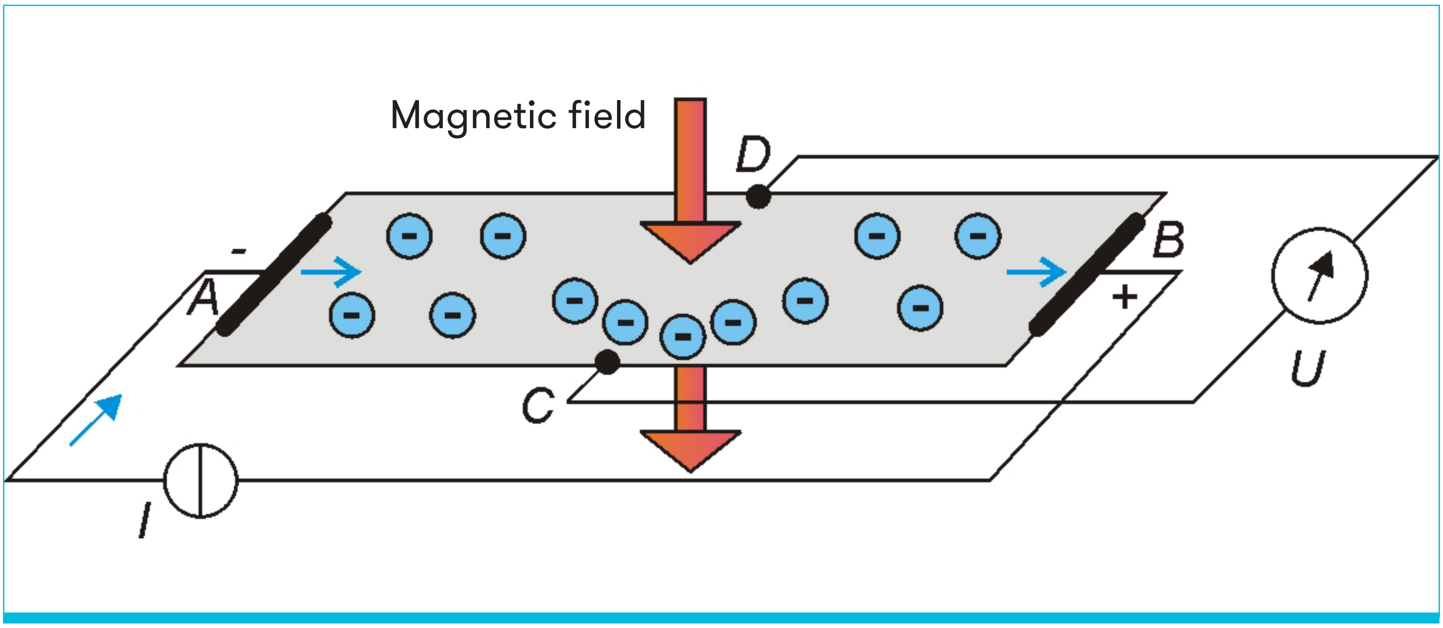

Fig. 5. Basic operating principle of a Hall sensor (image: Texas Instruments).

As mentioned, Ampere's law states that the magnetic field in the space around a conductor is proportional to the electric current flowing through that conductor. But which direction do the magnetic field lines follow? One method we can use to determine this is the right-hand rule. The magnetic field lines around a conductor form concentric circles, perpendicular to the conductor. Point the thumb of your right hand upwards in the direction of the current flow (from + to -), and your fingers will curve in the same direction as the magnetic field lines.

The direction of the magnetic field is important for magnetic current sensors because these components have a specific sensitivity axis. If the direction of the magnetic flux is not in its axis of sensitivity, they will not capture the field and will not produce a measurable output. As such, the sensors are usually sensitive to fields that run perpendicular to the front side of their housing.

All the various formats of magnetic current sensing use the same basic physics set out under Ampere's law. The difference is how the solution is mechanically and magnetically integrated: where is the field generated and measured relative to the current flow? This solution space can be roughly divided into three different types, depending on the mechanical integration.

Module-based sensing

Module-based sensing (Fig. 6) typically uses a magnetic toroid or other geometry to condense the magnetic field generated by the live conductor. The best-known examples of this design are current clamps for multimeters. (Fig. 7).

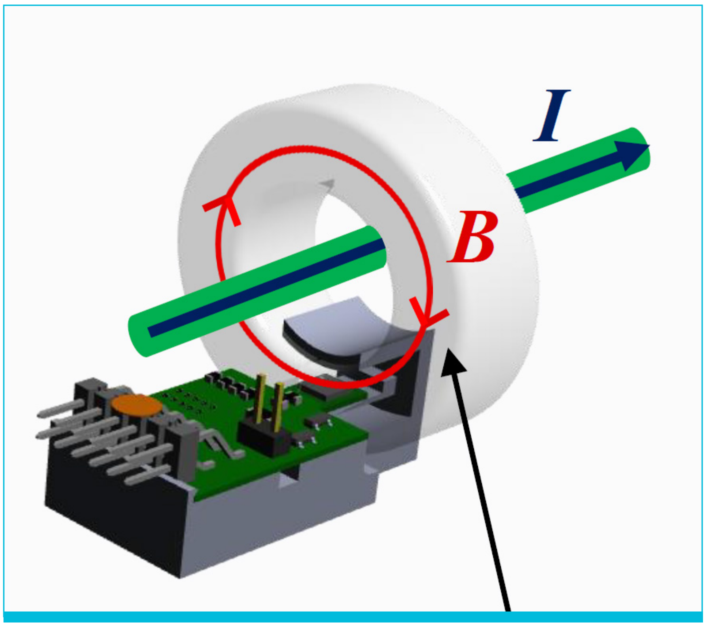

Fig. 6. Module-based sensing condenses the magnetic field. (Image: Texas Instruments)

Fig. 7. RS Pro ICMA1 clamp meter (image: RS Components)

Detecting the ambient field

Another use of magnetic current sensing is in the detection of the ambient field generated by a PCB trace, busbar or other conductor (Fig. 8). This is achieved using a linear Hall sensor at a fixed mechanical distance from the conductor. This solution can also use a magnetic condenser or shield to improve signal levels or reduce the effects of stray fields.

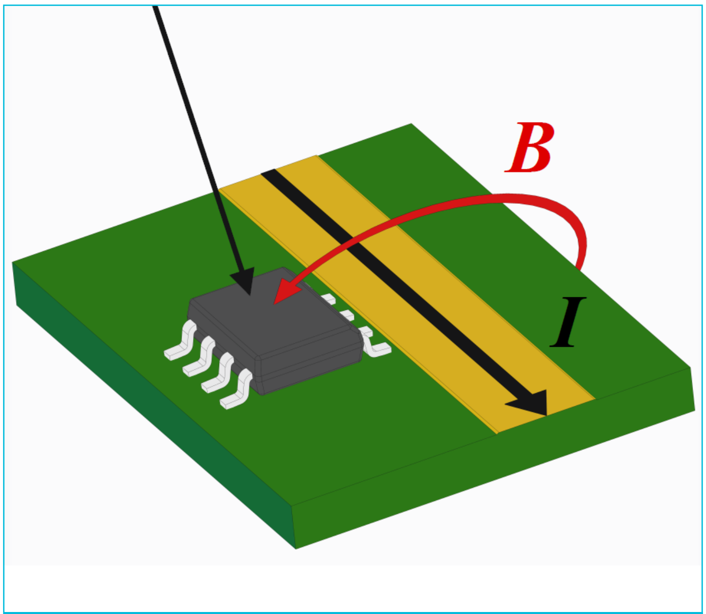

Fig. 8. Measuring current by detecting the magnetic ambient field (image: Texas Instruments)

In-housing detection

The third and final type is magnetic in-housing current detection (Fig. 9). With this technology, the monitored current actually flows through the device housing, and the magnetic field generated by the current flow through the conductor frame is measured internally using an isolated sensor IC.

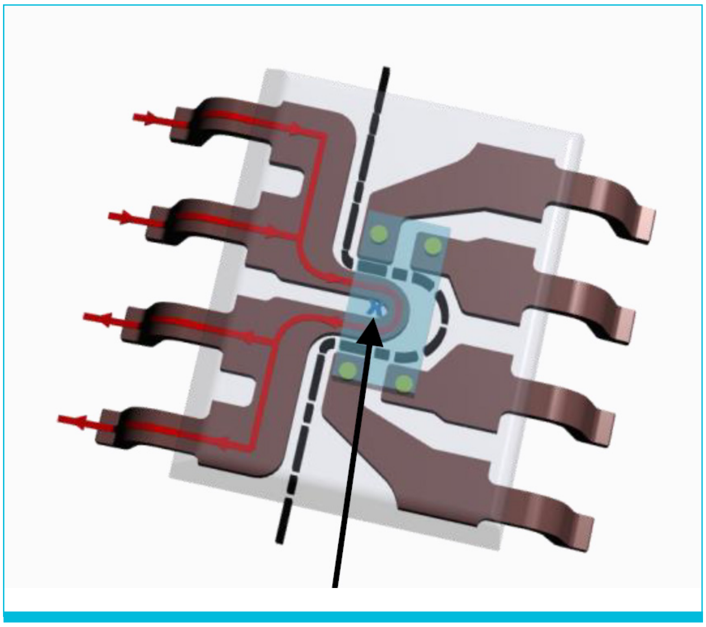

Fig. 9. Magnetic in-housing current detection (image: Texas Instruments)

What are the challenges of using magnetic current sensors?

It takes a vast amount of mechanical and magnetic engineering to develop one of these modules. This can be an unfamiliar area for engineers who usually work in electrics. While a module can create a powerful sensor solution, the complexity and costs associated with module design make it prohibitive for many applications.

Environmental sensors are affected by the distance to the magnetic field generated by the live conductor, while ambient and in-package types are both susceptible to interference from stray magnetic fields, other magnetic materials in the system, and the layout of the printed circuit. Magnetic in-housing current sensors come with several other unique challenges, including the finiteness of the insulation barrier and the thermal limits of their current sensing capabilities. There are solutions to these challenges. Stray fields, for example, can be resolved by using differential sensors or by shielding the sensor.

Summary

As demonstrated above, the supposedly simple current sensing by voltage drop at the resistor will always entail certain pitfalls. If these pitfalls are known, they can be avoided thanks to a wide range of measuring resistors – in terms of inaccuracy, resistor value and temperature behaviour. There is also an extensive range of amplifiers available, which means there is a suitable type for every measurement challenge.

In the past, magnetic current sensing was seen as a field of activity for absolute specialists. The market now offers very highly specified standard components, making the technology more approachable.

Based on documentation by Texas Instruments