Selecting the Most Effective Current Sensing Technology

When faced with selecting the most suitable method of accurate current measurement, a design engineer is faced with a number of possible alternative technologies. The selection of the most appropriate technology can often appear a little daunting. This article will assist the designer to the best choice for their specific application. **Warren Pettigrew, CTO Raztec Sensors, Christchurch, New Zealand**

Firstly, what are the necessary qualities that need to be considered? Of course product cost and the desired performance. The latter covers accuracy over current range (linearity, calibration, hysteresis); desired current range; acceptable output signal level; stability of offset over temperature range; stability of gain over temperature range; required frequency and transient response; satisfactory steady state signal to noise ratio and noise rejection from the primary circuit; stability over time; and satisfactory physical size. Other factors include compliance with appropriate standards; rated for application temperature range; acceptable level of heat generation, voltage and insulation rating and creepage distance of desired galvanic isolation, quiescent current, supply voltage, influence on the measuring circuit (impedance), and acceptable output resistance.

When considering the extensive (although, not exhaustive) list of qualities necessary, it becomes obvious that the design of current sensing is non-trivial and is often underestimated. This is further confounded by the number of available sensor options.

The most popular of the available technologies

There are numerous technologies available such as shunts, PCB track resistance, FET on-resistance, current transformer, Rogowski coil, open/closed-loop Hall effect sensors, or closed loop flux-gate. The task boils down to matching a technology to the need.

Something a designer really cannot afford to ignore is the time taken to design a product. If production volumes are small, normally a short design time is important so the selection of a simple, sure to work solution would be useful. To assist with the selection of appropriate technology, it should be possible to draw up a matrix matching qualities against the different technologies. However, such a matrix would be far too unwieldy. It is also complicated by the fact that appropriate technology changes with the level of current to be measured. Instead, the merits of each available technology, in turn, will be examined.

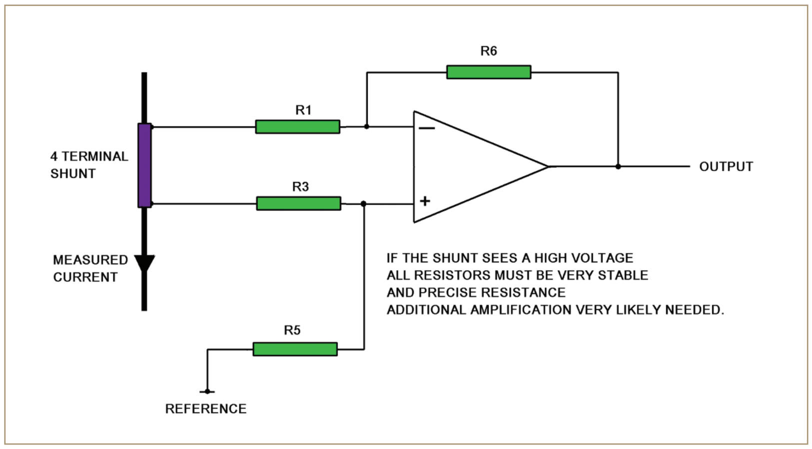


Figure 1: Basic shunt interface circuit

Shunts

If no galvanic isolation is needed, shunts are often the technology of choice for measuring ground referenced currents below approximately 20A. Performance can be improved by increasing the voltage across them (which, in turn, increases the need for heat dissipation), using a 4 terminal configuration, using a low inductance winding if high (100KHz) frequencies are to be measured, or interfacing with an op-amp which has low and stable offset voltage and high frequency response and high common mode rejection. If galvanic isolation is needed, opto-isolation can be incorporated, but this would then probably push costs higher than that of Hall sensors for all current ratings.

If the shunt is not ground referenced and is switched between ground and the

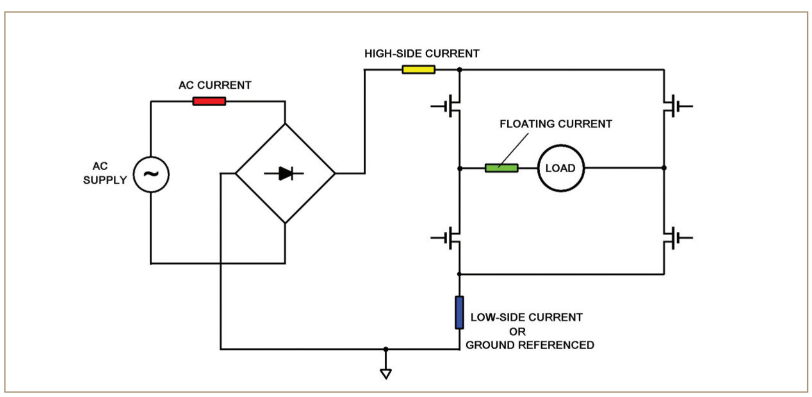


Figure 2: Various current sensing positions

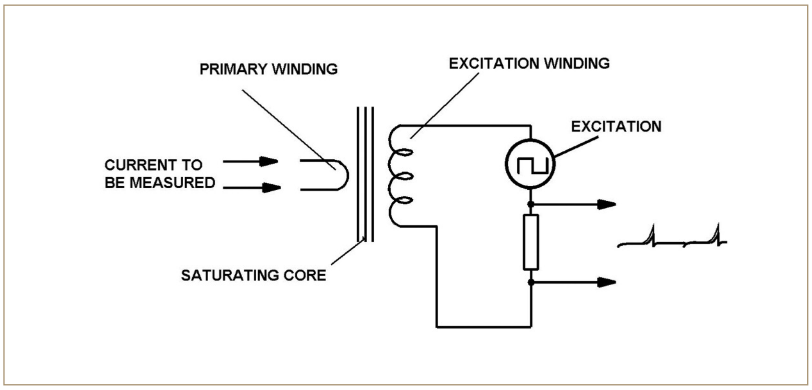


Figure 3: Simplistic DCCT

supply voltage, it is a distinct challenge for any operational amplifier to reliably see millivolts across the shunt with a relatively high common mode voltage - especially if the common mode voltage has PWM superimposed on it. One would be much better off choosing a galvanically isolated current sensor technology (see Figure 1).

For example, using the classical differential amplifier circuit, the shunt voltage can swing high R1>>R6 and R3>>R5 so that the op-amp is kept within its specified input voltage. However, if R1>>R6 and R3>>R5, the gain of the circuit is <<1 for a signal which is already small, it can be a challenge to re-amplify. Very stable, low noise amplifiers and resistors are needed. The amplification and noise suppression circuitry is likely to harm the frequency response and introduce significant phase shifts which, in turn can create instability. A Hall effect sensor is much easier to implement and is very likely to be cheaper than the combined shunt/amplifier configuration.

As the current gets higher, dissipation increases with an increase of footprint and cost.

For example, if we need to measure 100A and the minimum practical voltage that can be sensed is 0.2mV (noise limited) and we choose a 1mΩ shunt; its dissipation is 10W @ 100A and the minimum sensed current is 0.2A. An open-loop Hall effect current sensor would out-perform the shunt for size and cost, especially if the cost of the shunt's interface circuit is included. For any shunts, it is essential that thermocouple induced voltages are taken into effect – these WILL substantially limit dynamic range. Figure 2 shows various current sensing positions.

For non-critical applications and lower current applications, a piece of PCB trace can be used as a shunt. Its actual resistance would have to be calibrated, as there will be substantial batch to batch variation. Temperature compensation would probably also be necessary. The trace will be inductive, thus reducing its application for lower frequency measurements.

FET on-resistance

If your application allows you to get away with it, the cheapest current sensor is FET on-resistance. A FET is a resistor when turned on. However, there is a daunting array of variables such as gate-source voltage; junction temperature which is dependant on time, junction to heat-sink thermal resistance (device mounting pressure), ambient temperature, current (non-linear), or device characteristics. Despite all these issues, this technique is useful for detecting overload or desaturation of the FET.

Current transformers

These devices can only measure AC currents, but can do so very precisely over a wide dynamic range and up to high frequencies (>100KHz). Small units are cheap, offer galvanic isolation and are easy to interface to. They have good immunity to short-term overload, give negligible loading to the primary circuit and are self-powered. So what are their weak points?

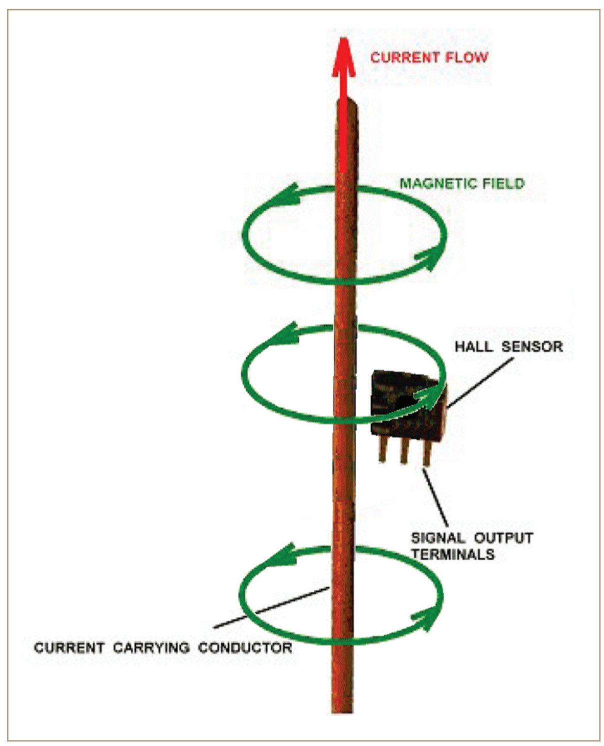
They don't like a DC component within the AC current that they are measuring. This causes saturation. However, there are special DC immune transformers, but this then often makes them more susceptible to stray magnetic fields. They can display non-linear phase shifts. Again, if special core material is chosen this effect can be reduced, but this then results in increased cost. Larger current devices are bulky, much more bulky than certain Hall effect based devices. There could be cost advantages in these sizes as well. Unless electrostatic shielding is fitted, primary voltage noise will inevitably appear on the output. Output voltage overshoot protection may be needed to protect the monitoring circuit.

Rogowski coil

A Rogowski coil is an air-cored current transformer. Its output is proportional to di/dt, so for it to generate a useful output an integrator is required to recover the current. By definition, they can't measure DC current, but are immune to DC current in the primary circuit. The coils themselves are cheap. They are often flexible, so they can be wrapped around a conductor. They are excellent for measuring high AC currents or high frequency currents.

So what are the downsides of using Rogowski coils? When required to measure low mains frequency currents, their outputs are minute. This results in the need for expensive amplifiers and an integrator to recover a useful signal. Dedicated interface

Figure 4: Hall sensing without magnetic circuit



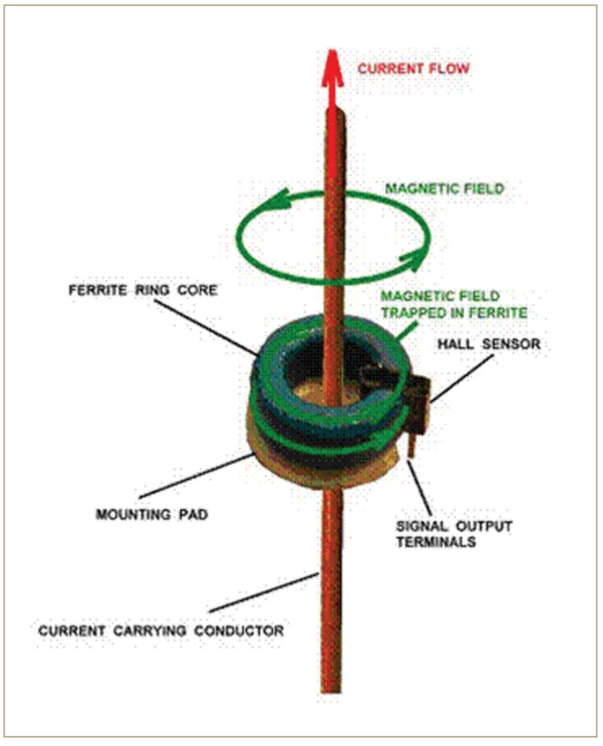


Figure 5: Hall sensing with magnetic circuit

circuits are available which claim operation over a wide dynamic range of current. Since signals are small, careful electrostatic screening will often be needed.

Direct current current-transformer

These sensors work on the principle that when a magnetic core saturates, it loses is inductance. A typical DCCT has an excitation winding wound onto a torroidal core which has enough excitation to just drive it into saturation. A primary conductor is passed through the core. The conductors current will modulate the core saturation which, in turn, will modulate the second harmonic of the excitation current. This is then the monitored output. For mains frequency applications, they can be excited using a sinusoidal mains frequency voltage. Figure 3 shows the DCCT principle.

As the name suggests, DCCTs can measure DC and AC currents with galvanic isolation. The strengths of these devices are simplicity and ruggedness against overload; if an appropriate core material is selected, they are sensitive to low (<20mA) currents; their offset is stable over a wide temperature range; and they offer good immunity to stray magnetic fields. But they don't have very good linearity; their frequency response is low (~500Hz) for a basic unit; they have limited dynamic range of current; and the output may carry excitation noise.

A single core design injects noise into the primary circuit.

Open-loop hall effect current transducers

These fundamentally simple devices can, with the selection of appropriate components, exhibit admirable performance. There are two distinct families:- units with a magnetic circuit and units without. The latter technology simply uses a magnetic field strength sensor to measure the flux surrounding a current carrying conductor (Figure 4).

This is very simple and generally low cost technology and is appropriate for some applications. Strong points are i.e. simplicity and low cost, providing galvanic isolation for measuring AC and DC currents; compact design especially when high (~150A) currents are to be measured; reasonable frequency response up to 50kHz; and good signal to noise ratio for high current sensing.

Weak points i.e. are very sensitive to stray magnetic fields. Even the earth's magnetic field gives a 0.5A error. Stray fields could arise from nearby conductors or contactor coils. Needs to be located very close to the current carrying conductor, this can then lead to insulation and electrostatic screening issues. Controlling the drift of offset voltage with temperature can be quite a challenge. Gain changes with temperature can be an issue.

The gain calibration of the devices will be very loose, as their output is very dependant on conductor position. This means that in-process calibration probably will be required.

This technology may be worth a look if it is necessary to measure reasonably high

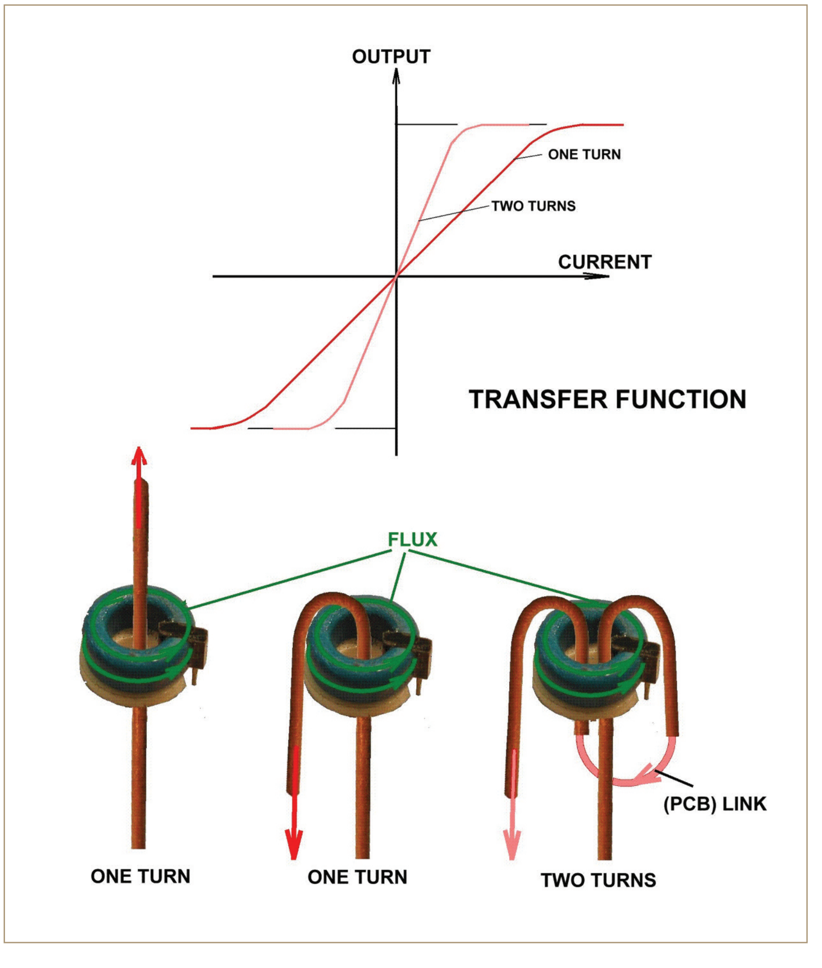
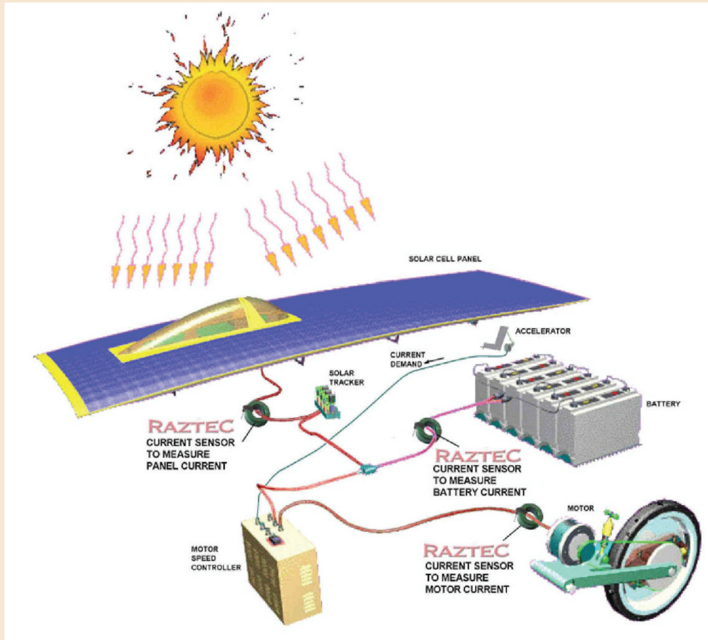


Figure 6: Effect of conductor passes through core

Raztec and the Solar Fern

The Panasonic World Solar Challenge is a biennial, friendly competition of solar and energy-efficient vehicles crossing between October 21 to 28 the Australian continent from Darwin to Adelaide in a 3000km trek. Now in its 20th anniversary year, teams came from across the globe, having researched, designed and built their own vehicles. Hall effect current transducers helped New Zealand's challenger for the World Solar Challenge.

Energy management and conservation are critical for the performance of solar powered vehicles. Energy flow is measured by monitoring voltage and current flow and Raztec Hall effect current transducers measure the current flow, as no loss is induced and readings are not disturbed by voltage in the current carrying conductor. For example, the preferred way to control motor power is to operate under torque mode control. Depressing the accelerator pedal demands an increase in torque from the motor in proportion to the angle of depression. To ensure that this process works consistently, the torque controller must monitor motor current quickly and accurately, and compare this with the demand from the accelerator - motor torque being directly proportional to current flow.



current cheaply and can tolerate imprecision.

Open-loop Hall devices with magnetic circuit (Figure 5) work on the same principle as the above sensors but, very importantly, include a magnetic circuit which concentrates the flux through the Hall magnetic field sensor. This action increases the relative precision by a factor 5 to 10 and greatly improves immunity to stray magnetic fields.

Advances in magnetic materials allow the selection of core materials that offer sharp saturation with little remanence and high saturation flux density. This can often result in better than 1% linearity over the rated current range. The selection of thermally stable Hall devices allow a practical dynamic current range of 2.5 decades, meaning a 100A sensor will be able to accurately measure down to 200mA.

In order to measure low currents, the primary can be passed multiple times around the magnetic circuit (Figure 6).

Strengths of this technology i.e. are compactness with very low loss method of measuring AC and DC currents; fundamentally simple low cost design; good immunity to stray magnetic fields; moderate quiescent current; good linearity; and temperature stable products. Most open-loop sensors have a moderate ~25KHz frequency response, but devices with bandwidths up to 350KHz are available providing reaction times of ~ 300ns and 90% primary current in ~1µs. These sensors feature a very easy interface with near rail to output voltage. Selected products have good signal to noise ratio and are rated for the automotive temperature range (-40 to 120°C).

Weaknesses i.e. are thermal drift of the quiescent voltage, and hysteresis may be a problem for some high precision

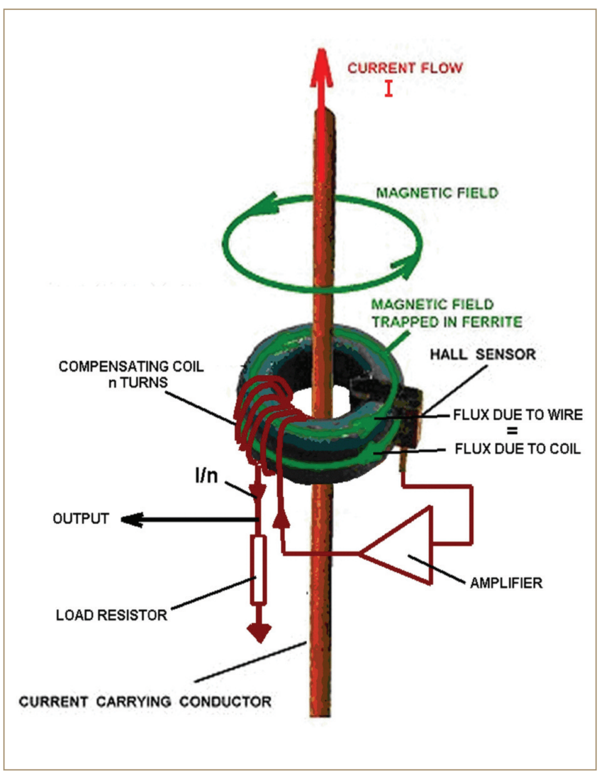


Figure 7: Closed-loop Hall effect current sensor

applications. In some low current applications, Hall sensors cost more than shunts or Cts. Some sensors may overheat if subjected to high frequency currents. Gain can change with temperature. A negative shift with increasing temperature could cause problems if the sensor was used for overload protection. Low cost sensors may require in-process calibration as their gain and offsets are commonly not tightly specified.

Open-loop Hall effect current sensors come in a variety of flavours. It is important that specifications are carefully reviewed so that the most appropriate sensor is selected. A reputable supplier can assist with their implementation.

There is a good chance that there will be an open-loop sensor that fits all your needs, but there are more options. It is possible to increase the current range of current sensors by shunting some current away from the sensor. However, this kills the frequency response as the high frequency component of the current passes through the shunt, bypassing the Hall sensor.

Closed-loop hall effect current sensors

These sensors work on a principle similar to the open-loop Hall sensors, but include a feedback winding to null the flux in the core (Figure 7). GMR sensors may be used in place of the Hall element. Because of the servo effect, excellent linearity results and gain become very independent of temperature. The feedback coil and associated amplifier does add some cost however.

The strong points i.e. are good DC and AC accuracy over a reasonable dynamic range. Low insertion loss; good frequency response (~100kHz); reasonable cost if a commitment made to ASICs; good immunity to stray magnetic fields and electric fields with suitable screening.

Weaknesses, in turn, are dynamic range limited in practice by core hysteresis and null drift with temperature; physically larger and costlier than open loop devices. Also, high quiescent current particular when the primary current is high. This makes for self-heating which, in turn, limits their use to lower ambient temperatures. These factors make them less attractive for automotive applications.

The performance of closed-loop sensors has stabilised, while that of open-loop continues to progress with the introduction of new materials and components. There are now few instances where closed-loop sensors are needed rather than their less costly open-loop counterparts.

Closed-loop flux-gate current sensors

If a compensating coil is added to a DCCT, its maximum operating range is no longer limited by core saturation; the compensating winding being excited to maintain the mean flux in the core to zero. However, two flux-gate cores working in opposition are needed to prevent excitation energy being transferred to the compensating winding (and the primary). If high frequency performance is needed, a CT can be added and its output added to the low frequency component from the flux-gate sensor. All this adds cost and complexity to the sensor, but these sensors may offer the most accurate current sensing available.

Strong points are i.e. very low hysteresis means that the sensors can measure very low (~50mA) currents with a single primary turn; with a closed loop compensating winding, hundreds of amps can be measured; very linear output over a reasonable dynamic range; very good signal to noise ratio; and if a high frequency winding is included, their frequency response is good.

Weaknesses i.e. are cost driven by complex magnetics and electronics; bulky; high quiescent current, particularly with high primary current, which makes for high self-heating which limits that applications to lower temperature environments; the compensating winding carries a lot of copper so it is expensive.

Conclusion

Selecting appropriate current sensing technology is complex and there are a great many options. Typical of engineering, most are imperfect. Continual progress in open-loop Hall effect current sensor technology means that the possible applications of these versatile devices continues to grow and displace other more traditional devices.